Reports
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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: July 17, 1974

Project Title: Conference on Fire Research

Project No: E-25-645

Principal Investigator Dr. S. P. Kezios

Sponsor: National Science Foundation

Agreement Period: From 5-1-74 Until 10-31-74 (Grant Expiration)

Type Agreement: Grant No. GI-44089

Amount: $10,000 (No cost-sharing required on Conference Awards)

Reports Required: Conference Report (Due NLT 90 days after Grant Expiration)

Sponsor Contact Person (s):

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RA-3 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY
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SPONSORED PROJECT TERMINATION

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9/15
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Date: March 13, 1976

Project Title: Conference on Fire Research

Project No: E-25-645

Project Director: Dr. S. P. Kezios

Sponsor: National Science Foundation

Effective Termination Date: 10/31/74

Clearance of Accounting Charges: 10/31/74

Grant/Contract Closeout Actions Remaining: None

- ___ Final Invoice and Closing Documents
- ___ Final Fiscal Report
- ___ Final Report of Inventions
- ___ Govt. Property Inventory & Related Certificate
- ___ Classified Material Certificate
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CA-4 (3/76)

PROCEEDINGS

NSF/RANN CONFERENCE ON FIRE RESEARCH
May 28-29, 1974

Hosted by

Georgia Institute of Technology
Atlanta, Georgia

General Chairman

Dr. S. Peter Kezios, Director
School of Mechanical Engineering

Program Chairman

Dr. Ben T. Zinn, Regents Professor
School of Aerospace Engineering

Local Arrangements Chairman

Dr. W. Denney Freeston, Director
School of Textile Engineering

FOREWORD

This document is a record of the fire research projects, supported by NSF, that were discussed at a conference on May 28 and 29, 1974, at the Georgia Institute of Technology. There is a brief progress report for each project. The report is not intended to provide all features of the research. Reports and publications are listed so that interested persons can obtain more information.

The NSF/RANN fire research effort has the objective to reduce deaths and losses due to hostile fires, and to improve the effectiveness of fire control. It has been in operation for three years, and currently the expediture level is about two million dollars per year. At this time, the future of the effort is uncertain, because it is dependent on actions to be taken by Congress and the administration.

When one looks at the cumulative results, I believe progress is evident and significant. The projects are in various stages of completeness. There are four comprehensive projects (Harvard, Johns Hopkins University/Applied Physics Laboratory, University of Utah, and University of California-Berkeley) which are much larger than the others. Thus the reports reflect such differences.

In addition to research performers, representatives of the fire protection community also attended the conference and participated in discussions. While the open and at times spirited interchanges were not recorded, they will surely be reflected in a strengthening of future research and thus meet a goal of the conference.

The Foundation welcomes comments on the fire research program and related needs. The dissemination of information from the projects to the various performers concerned with fire protection and control continues to be a matter of concern, and suggestions for improvement are solicited.

Ralph H. Long, Jr.
Program Manager
Division of Advanced
Technology Applications
National Science Foundation
1800 G Street, N. W.
Washington, D. C. 20550

NSF/RANN CONFERENCE

ON FIRE RESEARCH

Reorganization of this conference follows the intent of former conferences which is to provide a national forum for all researchers supported under the RANN programs involving fire research efforts to report their findings and exchange their views. The conference also provides a resource for other interested persons who identify strongly with the work in this general area. The summary of research efforts contained herein provide sufficient background so that both the purpose and structure of current research efforts in the field are clearly evident.

The RANN program of NSF and its commitment to the national needs involved in understanding and controlling undesirable fires has provided a nucleus of high grade research effort that augurs well for our nation's future ability to control and respond to fires which are unwanted as well as to reduce them in size and in their ultimate consequences.

In view of RANN's key role over the past several years it is proper that we recognize its importance in this research area and also that we thank the people who are central to this effort. A special word of appreciation in this regard must be extended to Dr. Ralph Long, Program Manager, Advanced Technology Applications Division, National Science Foundation, whose able administration of the programs could not have resulted only from his personal understanding and commitment to the members of fundamental approach to fire problems but also from his detailed technical knowledge from the problems themselves and of the people involved, and in his skill for emphasis on a combination of problems in personnel that would prove both effective and comprehensive.

The work of organization was greatly aided by Dr. Denney Freeston, Director of the School of Textile Engineering, who served as Local Arrangements Chairman, and Dr. Ben T. Zinn, Regents Professor in the School of Aerospace Engineering, who served as Program Chairman.

Dr. S. Peter Kezios, Director
School of Mechanical Engineering;
General Chairman, NSF-RANN
Conference on Fire Research

NSF/RANN

CONFERENCE ON FIRE RESEARCH

Session IV: Combustion Products Behavior (continued)

NSF/RANN Conference on Fire Research

Institution: University of California, San Diego NSF Grant No. GI-34775

Grant Title: FIRE PROPAGATION ALONG SOLID SURFACES

Principal Investigator: Professor Forman A. Williams
Department of Applied Mechanics
and Engineering Sciences
University of California, San Diego
La Jolla, California 92037
(714) 453-2000 Ext. 1609

Other Professional Personnel: Professor Paul A. Libby (Faculty)
Angel Fernández-Pello (Graduate Student)

Project Summary

Experimental and theoretical studies are performed on propagation of fire along flat surfaces of solid combustibles. The objectives are to identify conditions under which radiant, convective or conductive heat transfer is responsible for flame propagation and to investigate the importance of finite-rate chemistry. The plan of research is to make detailed experimental measurements of velocity, temperature and composition fields for steady spread over a small number of materials, to construct detailed theoretical models for describing the measured spread processes, and to pursue less thorough investigations, primarily theoretical, for categorizing combustibles with respect to their physical mechanisms of spread in various environmental configurations.

Progress Report

Preliminary tests, including studies of cellulose, polystyrene and polyformaldehyde, led to selection of polymethylmethacrylate (PMMA) as a prime candidate for detailed study because of its smooth burning. A variety of experimental and theoretical studies were completed for PMMA. First, by burning slabs of the material in O_2/N_2 flows, the dependence of the steady regression rate on surface temperature was found to be consistent with a theoretical prediction that employed kinetic data for bulk degradation in an asymptotic analysis for large activation energy. Next, steady flame spread in air, in directions ranging from downward to horizontal, was investigated experimentally. Downward spread rates were measured for sheets of thicknesses ranging from 1/32" to 6". For three different thicknesses, spread rates were measured as a function of the orientation angle of the sheet, for angles ranging from horizontal to vertical. Influences of backing materials on spread rates were measured, for highly insulating asbestos backing, for poorly insulating asbestos cement backing, anf for thin copper foil backing adjacent to insulating asbestos. Effects on spread produced by cutting small grooves in the PMMA and filling them with asbestos powder were investigated. Thermocouples were placed in the surface of the PMMA, and histories of surface temperature were recorded during spread over sheets of various thicknesses. Thermocouples were set in the interior of the PMMA so that complete mappings of the temperature field within the solid ahead of the flame could be obtained (see Fig. 1). Thermocouples were suspended at various distances above the surface of the PMMA, and temperature fields in the gas ahead of the flame thereby were obtained. These last results were checked by obtaining interferograms of the flow field by use of a Mach-Zehnder interferometer and using the interferograms to calculate temperature profiles. Radiant fluxes emanating from the flames were measured with a home-made radiometer and used to correct thermocouple temperature measurements. The shape of the flame, the shape of the burning PMMA surface and their relative locations were measured with high-magnification photography. Particles of MgO were injected into the flow ahead of the flame and photographed under stroboscopic illumination to obtain streamline shapes and approximate velocity profiles. Gas samples were withdrawn through sonic quartz microprobes and analyzed by gas chromotography to reveal the presence of the methylmethacrylate monomer ahead of the point of flame attachment.

Analysis of the flame-spread experiments with PMMA included formation of an energy balance for the solid by use of measured temperature fields. The calculations showed that ahead of the point of flame attachment, there was a close balance between heat conduction and convection in the direction of propagation. Radiant transport was negligible under most conditions. There was a small amount of conductive heat input from the gas near the point of flame attachment and a small amount of conductive heat loss to the cool inflowing gas farther upstream. Spread rates correlated well with histories of surface temperature under the assumption of an insulated upstream surface and an isothermal downstream surface. It was concluded that for downward flame spread over PMMA sheets, forward heat conduction through the solid is the major mode of heat transfer supporting spread. In this respect, PMMA differs from cellulose, for which forward heat conduction through the gas appears to be dominant. Also, for horizontal spread over PMMA the heat conducted in from the gas is a larger fraction of that conducted upstream through the solid. Thus, it is found that mechanisms depend on both the material and the configuration.

A theoretical model was developed for steady flame spread over PMMA sheets. The model involves thin diffusion-flame combustion in a downstream boundary layer, producing a nearly space-invariant downstream surface temperature, determined by a balance between heat conduction from the thin flame, heat required to pyrolyze the fuel and a kinetic relationship between the pyrolysis rate and surface temperature. The elevated surface temperature in the downstream region produces forward heat conduction, thereby raising the upstream surface temperature. In a thin upstream surface layer finite-rate pyrolysis of PMMA occurs, emitting monomer into a cool boundary layer generated by inflow into the flame plume. It is then suggested that thermal runaway of an ignition reaction for the fuel vapor may occur in this upstream boundary layer. Gas-phase temperature fields (Fig. 1) are qualitatively consistent with this final assumption, although quantitative confirmation through measurements of gas-phase ignition delay times is lacking. The theory predicts dependences of spread rate on sheet thickness, sheet orientation, atmospheric oxygen content and atmospheric pressure which agree approximately with existing data.

Accomplishments

1. Processes of steady flame spread in air over PMMA surfaces have been characterized experimentally much more thoroughly than ever before.

2. A qualitative theoretical model has been developed for describing the process of steady flame spread over PMMA surfaces. The predicted dependence of spread rate on experimentally adjustable parameters is in approximate agreement with experimental observations.

Potential Applications

Direct applications of results obtained to date must be restricted to early stages of fire development, ignition to flashover, during which time suppressive actions are most effective. The results provide accurate data on quantities such as spread rates, which in suitable configurations could control time to flashover. Detailed results to date are restricted to the combustible polymethylmethacrylate. In the long term, it is believed that by developing a thorough understanding of flame spread in an idealized situation, one will be able to better understand spread processes in the real world.

Future Milestones

In progress is development of an accurate and complete theoretical model for flame spread under conditions controlled by solid-phase heat conduction. This is intended to quantify the approximate physical model described earlier. Asymptotic analyses, with nondimensional activation energies treated as large parameters, are being pursued. These analyses should result in accurate formulas for spread rates, applicable to conditions under which the model is correct.

A small amount of further experimental testing is planned. This includes application of one or two additional techniques to PMMA and much less detailed studies of other materials.

Theoretical work is planned on identifying conditions under which different modes of heat transfer produce flame spread. Approximate theoretical categorizations, with broad applicability but reduced accuracy, are expected to be obtained. The results should have much wider use than those developed to date in the present program.

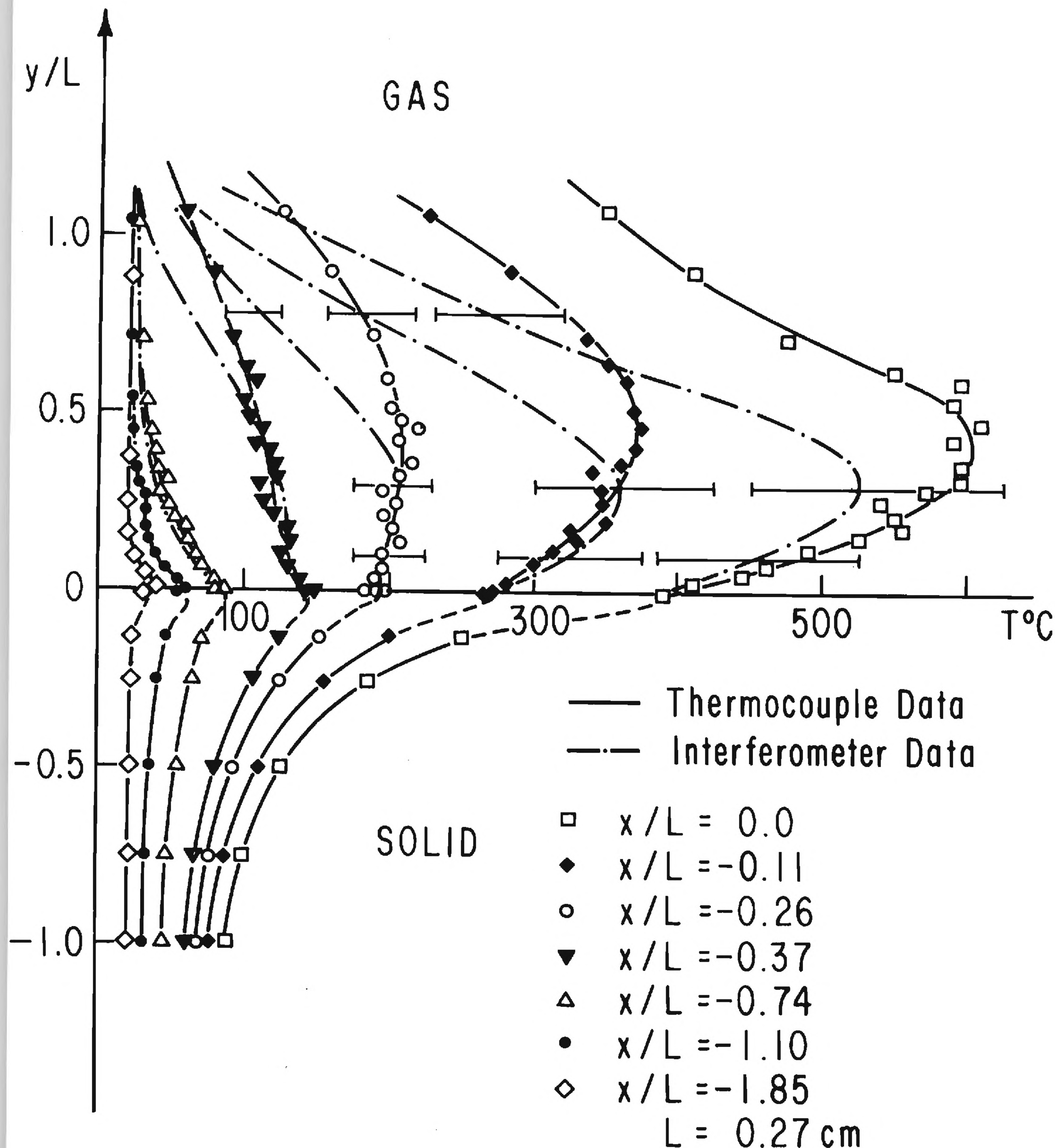
<u>Reports</u>

L. Krishnamurthy and F. A. Williams, "On the Temperature of Regressing PMMA Surfaces", Combustion and Flame <u>20</u>, 163-169 (1973).

A. Fernández-Pello, M. Kindelan and F. A. Williams, "Distribucion Superficial de Temperaturas Durante la Propagacion de Llamas en Sentido Descendente Sobre Laminas de PMMA", <u>Ingenieria Aeronautica y Astronautica</u>, to appear (1974); see also Western States Section, Combustion Institute, Preprint No. WSS/CI 73-8.

A. Fernández-Pello and F. A. Williams, "Laminar Flame Spread over PMMA Surfaces", to be presented at Fifteenth Symposium (International) on Combustion, Tokyo, August 1974.

Figure 1 Temperature fields upstream from the point of flame attachment for vertically downward burning of PMMA sheets of half-thickness 0.27 cm.



y/L
GAS
1.0
0.5
0
-0.5
-1.0
100
300
500
T°C
Thermocouple Data
Interferometer Data
SOLID
x / L = 0.0
x / L =-0.11
x / L =-0.26
x / L =-0.37
x / L =-0.74
x / L =-1.10
x / L =-1.85
L = 0.27 cm

BROWN UNIVERSITY

Institution: Brown University NSF Grant No. GI-41514

Grant Title: Flame Spreading Over Solid Surfaces

Principal Investigator: Merwin Sibulkin, Division of Engineering, Brown University, Providence, R.I. 02912, (401)863-2867

Other Professional Personnel: Michael Little, graduate student; Jeongbin Kim, graduate student

PROJECT SUMMARY:

The primary objective of this research program is to obtain experimental and analytical results which enable fire protection engineers and fire fighters to make quantitative predictions of fire growth rates. A quantitative knowledge of fire growth rates has the potential of leading to improvement of the fire safety aspects of building codes. An understanding of the theoretical basis of flame spreading should lead to more rational ways of testing the relative flammability of different materials. In the case of a fire, the ability to predict fire spread rates is important to determine the magnitude of the blaze the fire fighter will confront and the time available for safe evacuation of building occupants.

An objective of a portion of this program is to extend our investigations of flame spreading to near extinguishment conditions. The goal of this portion of the work is not measurement of the flame spread rates themselves, but to obtain an understanding of why materials will not sustain a flame under certain conditions. The desired application of this work is to improve the engineer's ability to design nonflammable structures and, if possible, to suggest improved methods of extinguishing fires.

PROGRESS REPORT:

The study of flame spreading on a horizontal, thermally thick PMMA fuel bed reported on last year has been concluded. For a pyrolysis zone diameter $d_p > 5$ cm, the flame spreading rate was independent of flame size (up to extinguishment at $d_p = 18$ cm). The flame spreading rate for nine runs was $V = .00502$ cm/sec with a standard deviation $s = .00011$ cm/sec showing the repeatability of the phenomena. Mass loss measurements made by weighing the sample before and after burning show that Δm varies as $d_p^{2.7}$. The rate of mass loss per unit area has been calculated and compared with the data of Blackshear and Murty for steady pool burning.

Surface temperature profiles were made using Pt-Pt 10% Rh thermocouples having diameters of .010", .003" and .001" to evaluate the effect of wire diameter on the measurements. The thermocouples were laid along portions of circular isotherms to reduce conduction errors. The surface temperature T_s rose very slowly until the flame was close (≈ 0.5 cm) to the thermocouple, and then rose rapidly to a maximum value of about 410°C when the edge of the pyrolysis region reached the thermocouple. When T_s is plotted versus distance ahead of the pyrolysis zone $(d_{TC} - d_p)/2$ for $d_p = 5$, 10, and 15 cm, the resulting profiles are essentially independent of d_p. The preheat distance δ_T (based upon the tangent to T_S) is 0.18 cm. Thus, for $d_p \geq 5$ cm, the relative thickness of the preheat zone $\delta_T/d_p << 1$. This result suggests that our results should be equivalent to those for propagation of a planar flame front over a thermally thick fuel bed. The observed constant value of the flame spread rate V supports this interpretation. Further support is given by flame propagation measurements for two-dimensional burning of 12" wide, horizontal sheets of PMMA of several thicknesses by Williams whose values of V approach our thermally thick value as the sheet thickness increases.

A comparison of the temperature profile for horizontal burning with that previously found for vertically downward burning of a cylinder (Sibulkin and Lee) and slab (Fernandez-Pello et al.) shows a marked similarity (Fig. 1). The higher surface temperature of the horizontal plate which is observed as the distance ahead of the flame increases is attributed to radiation from the flame to the surface. This interpretation has been supported by a radiation measurement.

High-speed photography has shown an interesting oscillatory aspect of the burning process. The oscillations do not appear, however, to affect the rate of flame propagation.

We have divided the problem of deriving a theory of flame spreading into two stages: (i) the calculation of the flame spread rate V for a specified surface heat flux distribution $\dot{q}''(x)$ by a solid phase analysis, and (ii) the prediction of $\dot{q}''(x)$ by a gas phase analysis. The models used in the solution of problem (i) are shown in Fig. 2. The two-dimensional heat conduction equation has been solved for the specified boundary conditions by a Fourier transform technique. Evaluation of the inversion integral gives a temperature distribution which depends parametrically on V. A unique value of V is determined by the condition that the surface temperature reaches the pyrolysis temperature at the leading edge of the flame. The results are presented in Fig. 3 in terms of non-dimensional velocities $V\tau/\alpha$ and $V\delta/\alpha$ and heat input $\dot{q}''(0)\delta/k(T_p - T_\infty)$ for a range of values of the thickness parameter δ/τ. (The symbols δ, τ and $\dot{q}''(0)$ are defined on Fig. 2; k is the thermal conductivity, α the thermal diffusivity, and T_p the pyrolysis temperature.)

Measured values of V and δ for a range of slab semi-thickness $\tau = 0.013''$ to 3" have been used to calculate $\tilde{\delta}$, $\tilde{V}$ and $\hat{V}$; these experimental values are superimposed on the analytical curves in Fig. 3. The measurements cover a range of $\tilde{\delta}$ from nearly thermally thin to the thermally thick limit, and give a non-dimensional heat input ahead of the flame $\hat{q}$ which has a relatively small range of variation. This result, if confirmed by further experiments, would simplify the theory of flame spreading.

ACCOMPLISHMENTS:

Measurements of flame spreading rates on PMMA rods have shown the effects of fuel specimen size and orientations. The results show the importance of geometrical effects in addition to those of material properties. A detailed energy balance analysis has given the magnitude of the energy feedback rate to the unburned fuel which propagates the flame.

An analysis has pointed out the effect of flame size on the type of radiation from flames. The fraction of the energy of combustion emitted as radiation is shown to increase with increasing flame size.

Measurements have been made of the characteristics of flame spreading from a local source of ignition on a vertical surface.

The rate of flame spreading on a horizontal surface has been shown to be nearly independent of the size of the burning region. Surface temperature profiles ahead of the flame show a small ratio of preheat distance to flame radius providing a physical basis for the constant propagation velocity.

An analysis of the solid phase portion of the flame spread problem for finite thickness slabs gives flame propagation rates based on a purely thermal criterion. A comparison with measured propagation velocities and surface temperatures gives an estimate of the heat input rates.

POTENTIAL APPLICATIONS:

Measurements of burning on vertical surfaces may be used as the basis for a more realistic small scale test for housing materials.

The similarity of measured temperature profiles ahead of the flame for several burning configurations provides a basis for a simplified approach to downward and sideward burning.

FUTURE MILESTONES:

Extension of the thermal theory of flame spreading to axisymmetric fuel specimens.

Analysis of the gas phase portion of the propagating flame including the induced velocity field.

Measurements of flame spreading under near extinguishment conditions, and a comparison of the effectiveness of fire extinguishants.

REPORTS:

1. "Estimates of the effect of flame size on radiation from fires," by M. Sibulkin. *Combustion Science and Technology* 7, 141 (1973).

2. "Flame propagation measurements and energy feedback analysis for burning cylinders," by M. Sibulkin and C. K. Lee. *Combustion Science and Technology* (in press).

3. "Flame spreading from a point source on a vertical wall," by A. Hansen and M. Sibulkin. *Combustion Science and Technology* (in press).

4. "Effects of orientation and external flow velocity on flame spreading over thermally thin paper strips," by M. Sibulkin, W. Ketelhut, and S. Feldman. *Combustion Science and Technology* (in press).

5. "Burning on a horizontal, thermally thick PMMA fuel bed," by M. Sibulkin and A. Hansen (in preparation).

6. "The dependence of flame propagation on surface heat transfer," by M. Sibulkin, J. Kim and J. Creeden (in preparation).

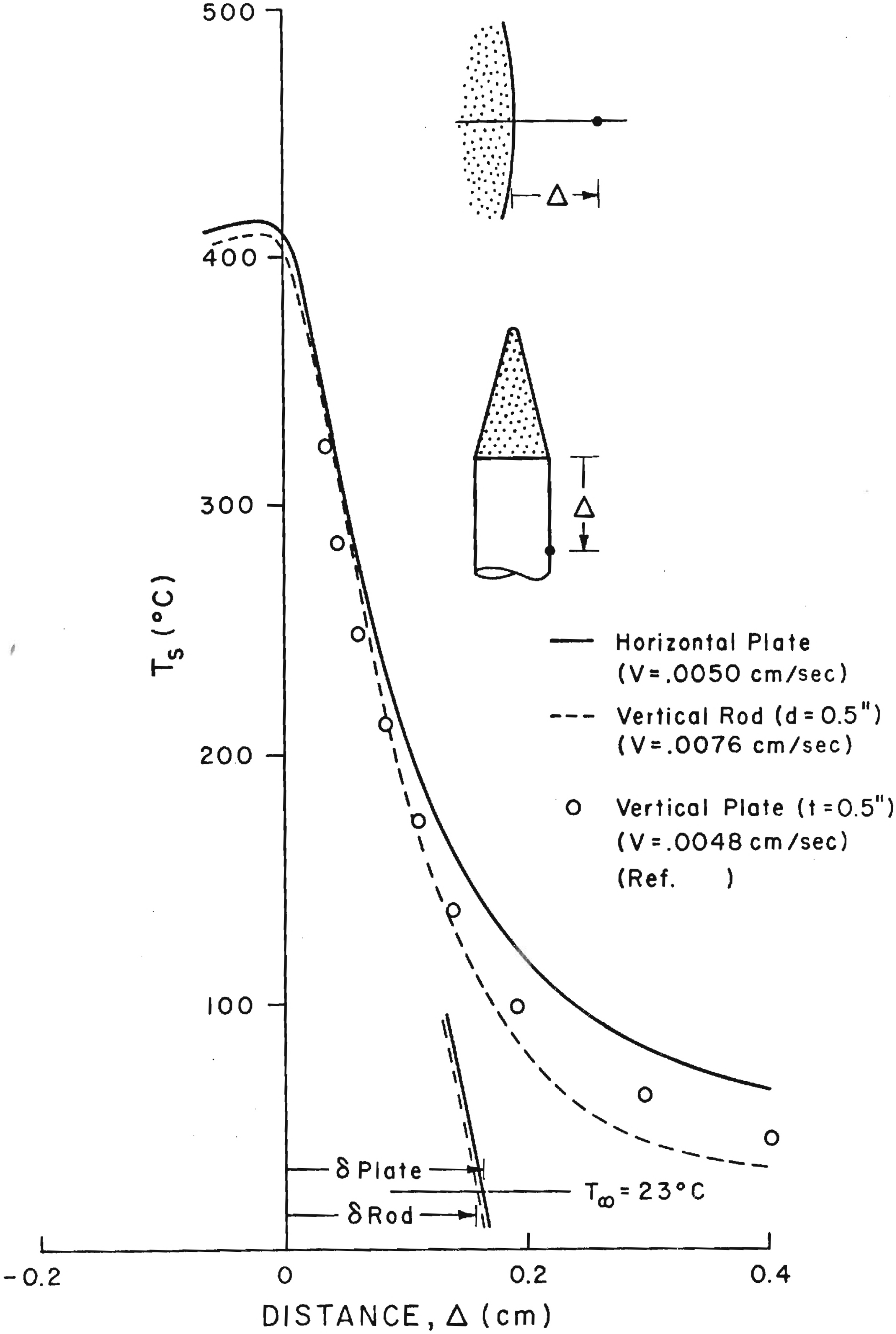

500
400
300
200
100
T_s (°C)
Horizontal Plate
(V=.0050 cm/sec)
Vertical Rod (d=0.5")
(V=.0076 cm/sec)
Vertical Plate (t=0.5")
(V=.0048 cm/sec)
(Ref.)
δ Plate
δ Rod
T_∞ = 23°C
Δ
-0.2
0
0.2
0.4
DISTANCE, Δ (cm)

Fig. 1

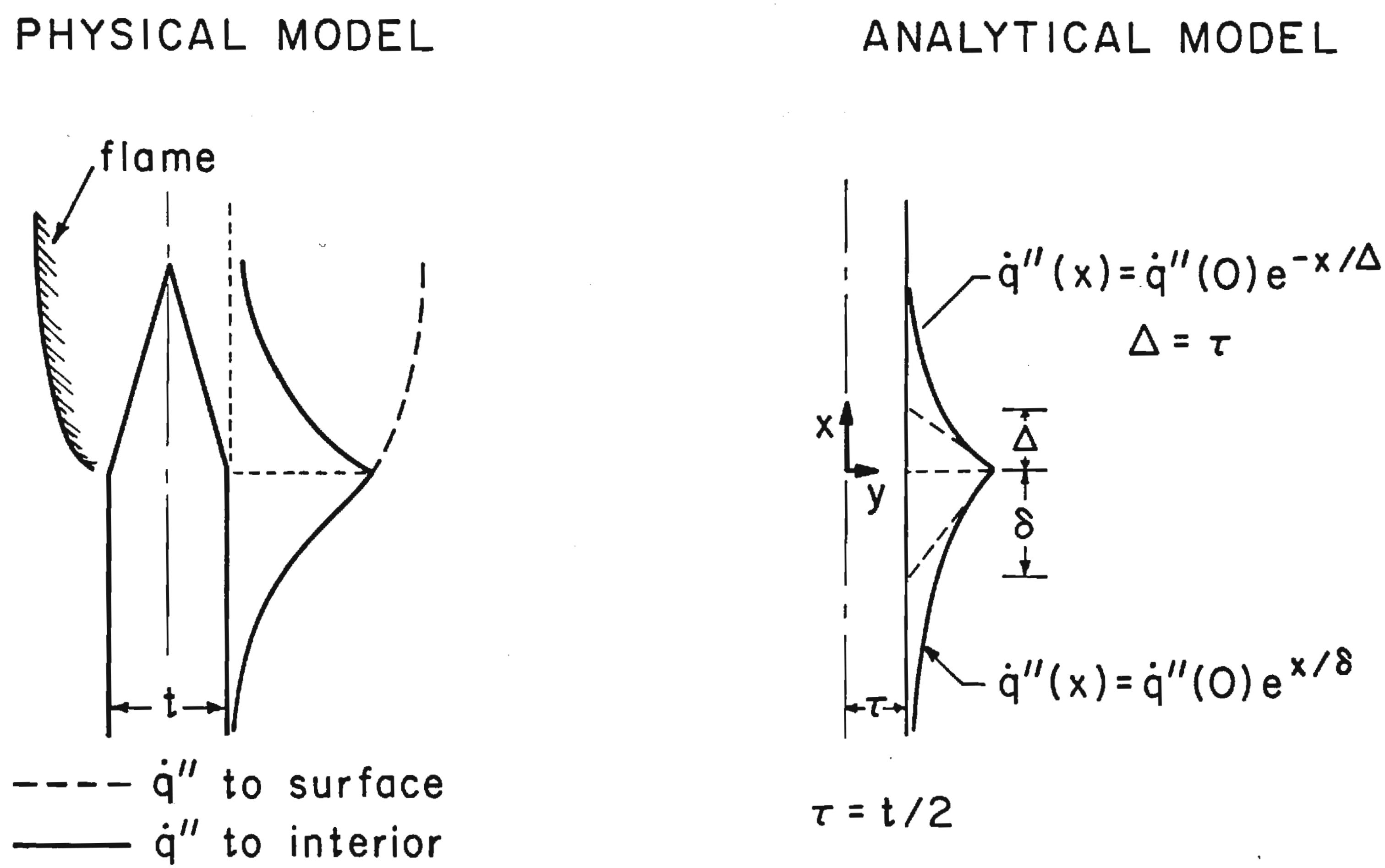

PHYSICAL MODEL
flame
t
---- $\dot{q}''$ to surface
—— $\dot{q}''$ to interior
ANALYTICAL MODEL
$\dot{q}''(x) = \dot{q}''(0)e^{-x/\Delta}$
$\Delta = \tau$
x
y
Δ
δ
τ
$\dot{q}''(x) = \dot{q}''(0)e^{x/\delta}$
$\tau = t/2$

Fig. 2

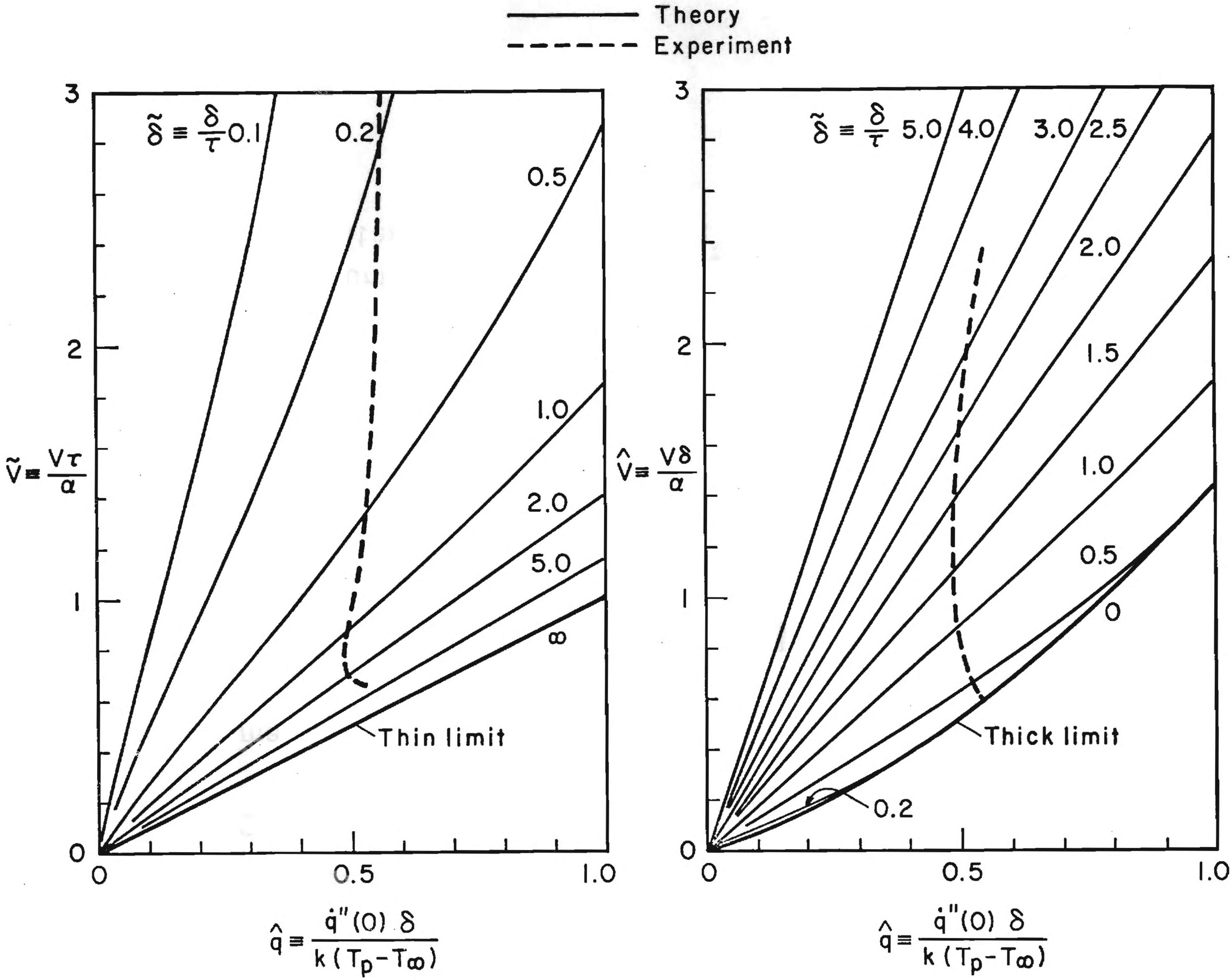

Theory
Experiment
$\tilde{\delta} \equiv \frac{\delta}{\tau}$ 0.1
0.2
0.5
1.0
2.0
5.0
∞
Thin limit
$\tilde{V} \equiv \frac{V\tau}{\alpha}$
$\hat{q} \equiv \frac{\dot{q}''(0)\,\delta}{k\,(T_p - T_\infty)}$
0
0.5
1.0
1
2
3
$\tilde{\delta} \equiv \frac{\delta}{\tau}$ 5.0
4.0
3.0
2.5
2.0
1.5
1.0
0.5
0
0.2
Thick limit
$\hat{V} \equiv \frac{V\delta}{\alpha}$
$\hat{q} \equiv \frac{\dot{q}''(0)\,\delta}{k\,(T_p - T_\infty)}$
0
0.5
1.0
1
2
3

Fig. 3

UNIVERSITY OF UTAH

Report To

NSF/RANN Conference on Fire Research

Atlanta, Georgia, May 28-29, 1974

Department of Chemical Engineering
University of Utah

NSF Grant Number
GI-39753

Grant Title: MECHANISM OF FIRE PROPAGATION ON POLYMER SURFACES

Personnel:

Principal Investigators:

Professor A. D. Baer (801) 581-6918

Professor N. W. Ryan (801) 581-7735

Department of Chemical Engineering
University of Utah
Salt Lake City, Utah 84112

Ph. D. Candidate:

Joseph W. Lindsey

Project Summary

The objective of the project is to investigate the contribution of chemistry to the phenomenon of flame spread, which has been treated by other workers as a strictly thermal process. The procedure is to study the native pilot flame--the small, fuel-lean flame leading the main flame across the surface. The basic hypothesis is that the air flow induced by the flame separates from the surface and provides a vortex which exchanges oxygen and fuel fragments between the air and the fuel surface; and, further, that the fuel fragments are the products of oxidative pyrolysis.

Progress Report

The pioneer experiments have been of two kinds. In one, the flow field ahead of the flame has been simulated in water-table experiments, and the existence of the vortex attending flow separation confirmed. Quantitative translation of the observations to the air-flow situation is yet to be attempted.

The other experiments have dealt with flame-spread over polymer surfaces. Flame spreads readily over PMMA, but not, under atmospheric conditions, over polyethylene, PVC, or a polycarbonate. On PMMA, the native pilot flame is quite pronounced. Flame-spread rates have been measured.

Potential Applications

The work in progress and that planned for the near future is laying the necessary foundation for future effort concerned with the chemistry of flame spread. The applications will be in making polymers safer by chemical modification.

Future Milestones

Milestones ahead, or presumed to be ahead, are (1) adequately characterizing the native pilot flame, (2) probing the flame to learn its chemistry-transport nature, and (3) applying the technique broadly and generalizing the results.

Reports

None have been generated as yet.

UNIVERSITY OF MAINE

NSF/RANN Conference on Fire Research
20 May 74

Institution; University of Maine
Orono, Maine 04473

NSF Grant GI-35509

Grant Title; Fire Rate of Spread in Paper Arrays

Principal Investigator; Ashley S. Campbell
Dept. of Mechanical Engineering
(207) 581 7125

Other Professional Personnel; David Reid Grad Asst.
Antoine Sirfan "

Project Summary;

The purpose of the study is to examine the behavior of a free-burning fire which is spreading through an array of uniformly spaced, free-standing sheets of filter paper. The fuel array is discontinuous, and the fire spreads by "jumping" from sheet to sheet.

Accomplishments;

The experimental arrangement is illustrated in Fig 1. The spacing distance between sheets is S. The height of the sheet exposed to burning is H. The spacers between sheets are not solid, but are constructed with four protuberances so that air may flow into the array from below through the spaces between protuberances. Side walls prevent the fire from propagating along the vertical edges of the sheets.

The array is ignited at the mid-point of the top edge of an end sheet. The jump time Δt is measured. A thermocouple is imbedded at the mid-point of the top edge of a sheet at least 7" away from the ignition sheet.

The temperature trace recorded by the thermocouple is indicated in Fig 1. Heat transfer by radiation begins when the burning zone is about 6" from the thermocouple. The heating rate increases slowly as the fire advances. The heating rate increases enormously when the fire front arrives at the sheet adjacent to the thermocouple.

The temperature at the knee of the curve is denoted by T^*. For small S values, the knee is sharply defined. For large S values the transition between the two heating regimes is gradual.

The variations in spread rate V and T^* are shown in Fig 2. The limits of propagation are also indicated. Presumably, propagation could be extended to larger S values by increasing H, since for large H the burning time of each sheet in the array is large, which increases the size of the burning region, which in turn increases the rate of heat transfer to the unburned sheets.

Assuming an ignition temperature of 325 C, the overall heat flux from the burning zone to the unburned sheet which ignites next may be calculated by dividing the jump time into the enthalpy rise from T^* to 325 C. The variation of the overall heat flux so defined is shown in Fig 3. The dependence on S is significant; the dependence on H is negligible.

We wish to see if we can duplicate the temperature-time history in the radiant heating regime. This requires information on the radiation intensity of the flames, and the manner in which the intensity is distributed over the flame surface. By burning a number of sheets, arranged parallel to each other, in a downward direction so that the flame region passes in front of a heat flux sensor which views the flame through a small water cooled rectangular aperture, we get the preliminary data shown in Fig 4. The left-hand set of curves illustrate heat flux variation at the base of flames produced by different numbers of sheets, with the same spacing. The right-hand set of curves show the heat flux variation when three sheets are burned with various spacing distances between sheets. (The discrepency between the two sets of curves arises because of different position of the sensor.)

The detailed study of the intense heating regime in which convection and conduction between flame surface and sheet dominate, and account for about three quarters of the necessary heat transfer, appears to be rather difficult because of the transient nature of the burning region. Fig 5 represents the essential details of the propagation of a burning zone consisting of three sheets, moving from left to right. In (a) sheet D is about to ignite, and when it does, the flame first appears on the back side, as indicated in (b). An instant later the flame has climbed over the top of sheet D, producing the small flame shown in (c). The small flame grows quickly, merges with the flame on sheet C, as in (d), producing an intense heating rate in sheet E, while sheet A burns out. Due to the rounded shape of the flame on sheet D, the heat flux to sheet E increases as the flame travels down sheet D.

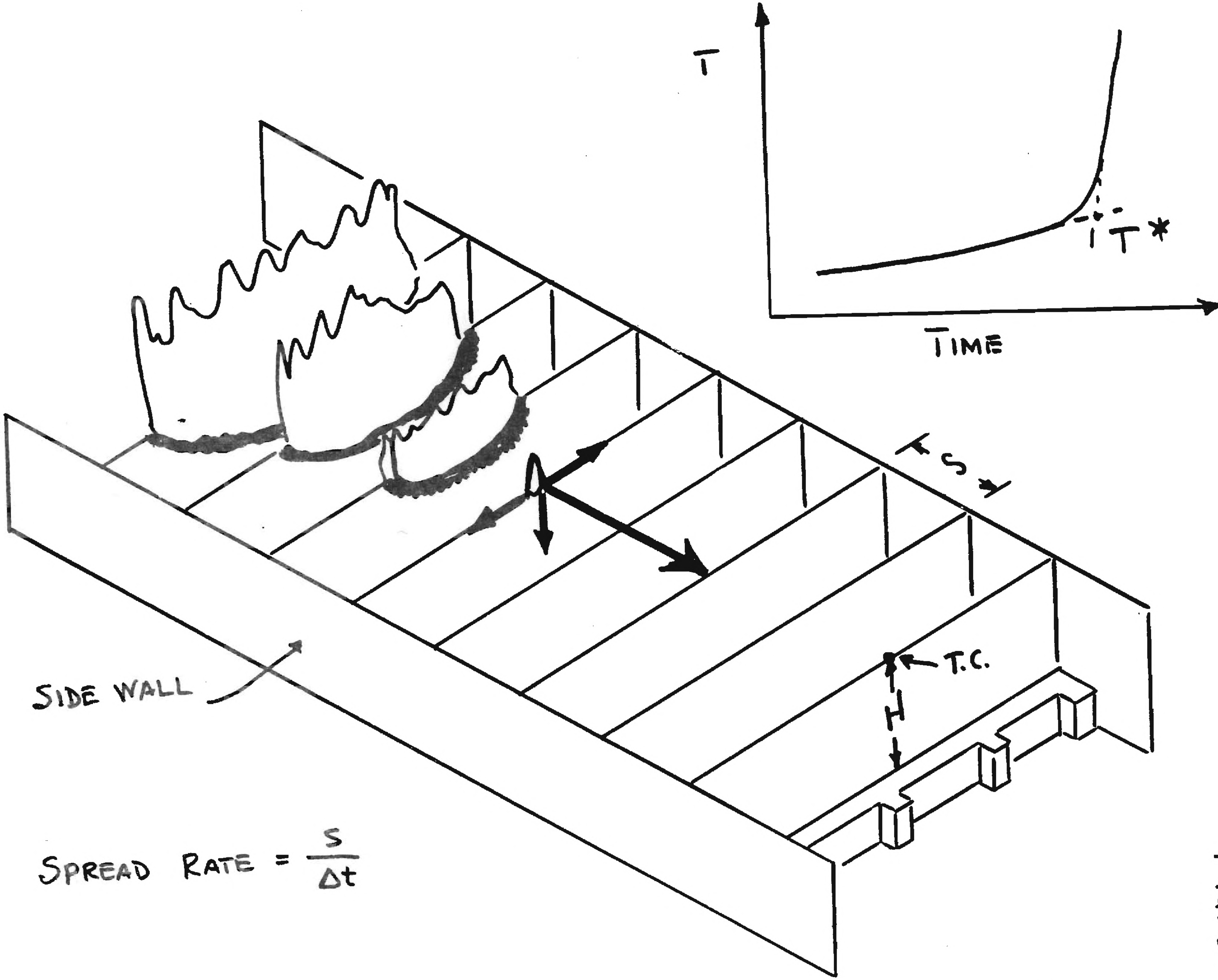
Potential Applications

The study of this simple laboratory fire serves to identify the two main problems involved in formulating a general theory of fire spread. The first is the part which flame radiation plays in heating the unburned fuel. In the present study, radiation contributes as much as one third of the heating requirement. The second is the large influence spacing between sheets exerts on the rate of heat transfer between flame surface and the adjacent unburned sheet.

Reference:

A similar study of fire spread along a single file of vertical matchsticks has been reported:

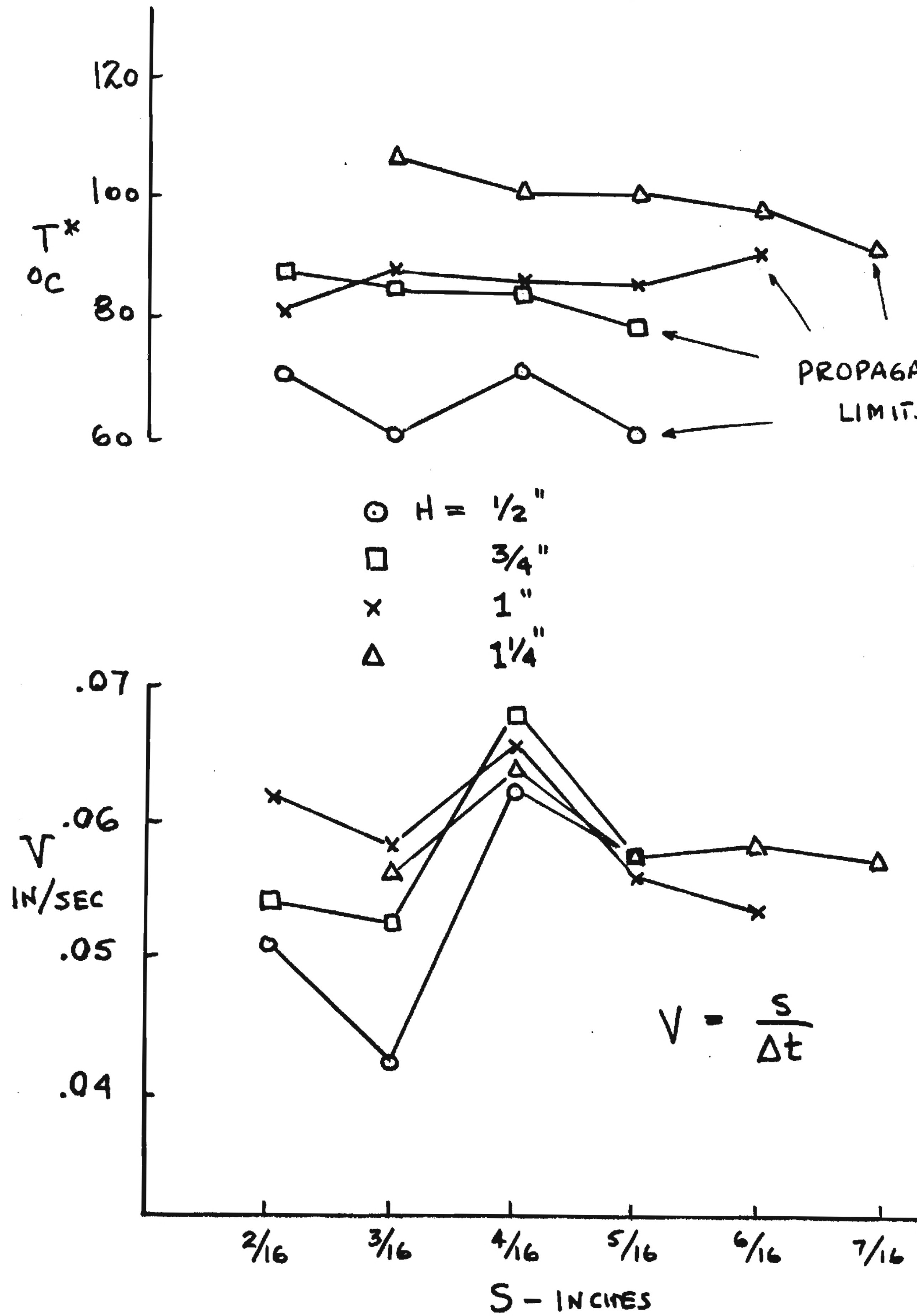
Flame Propagation Along Matchstick Arrays
Vogel and Williams, Combustion Science and Technology, Vol1, No 6 (1970).



SPREAD RATE = $\frac{S}{\Delta t}$

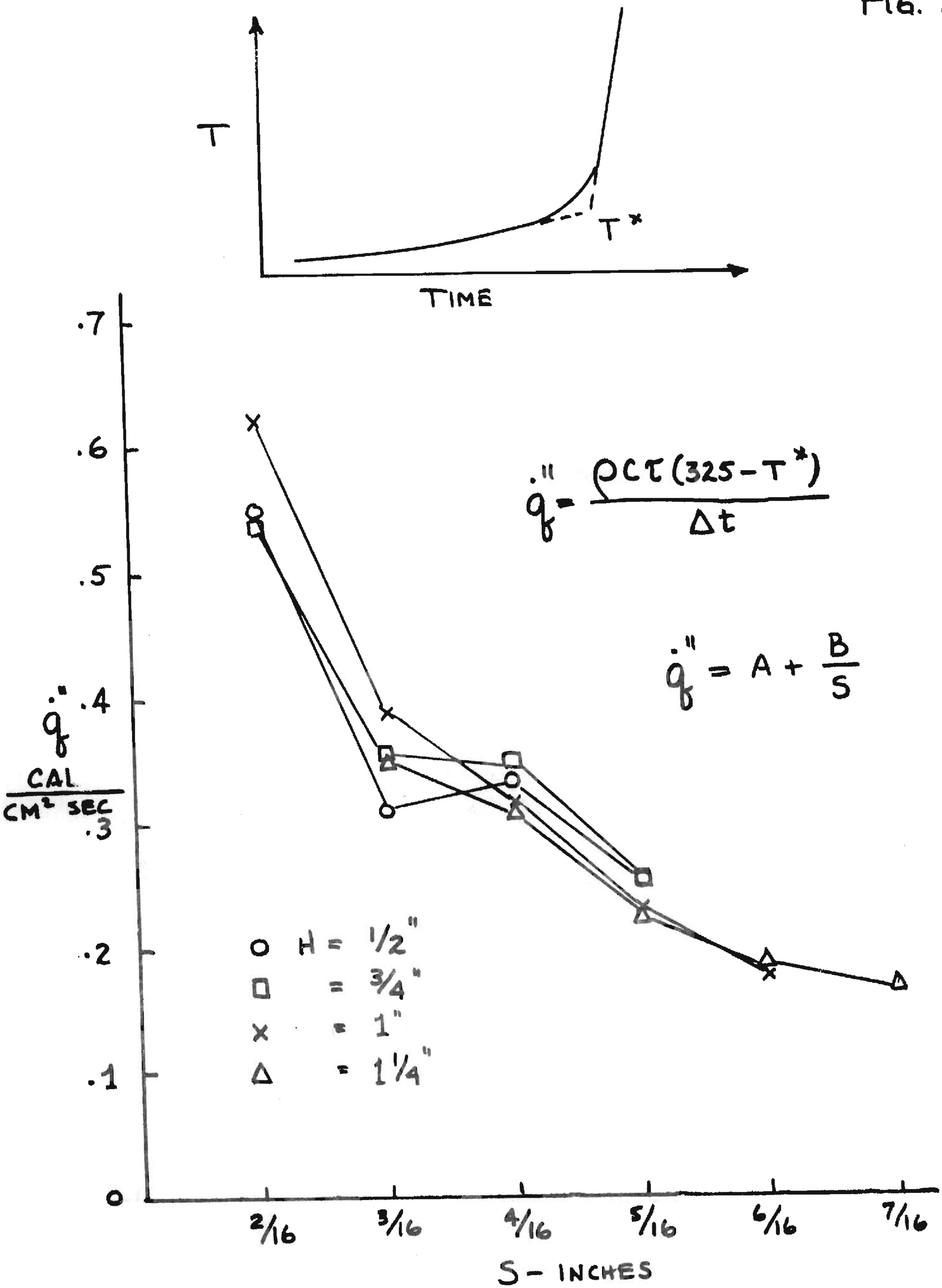
FIG. 1

FIG. 2



120
100
80
60
T*
°C
PROPAGATION
LIMITS
H = 1/2"
3/4"
1"
1 1/4"
.07
.06
.05
.04
V
IN/SEC
V = S/Δt
2/16
3/16
4/16
5/16
6/16
7/16
S - INCHES

FIG. 3



T
T*
TIME
$\dot{q}'' = \frac{\rho c \tau (325 - T^*)}{\Delta t}$
$\dot{q}'' = A + \frac{B}{S}$
$\dot{q}''$ $\frac{CAL}{CM^2\ SEC}$
.7
.6
.5
.4
.3
.2
.1
0
○ H = 1/2"
□ = 3/4"
× = 1"
△ = 1 1/4"
2/16
3/16
4/16
5/16
6/16
7/16
S – INCHES

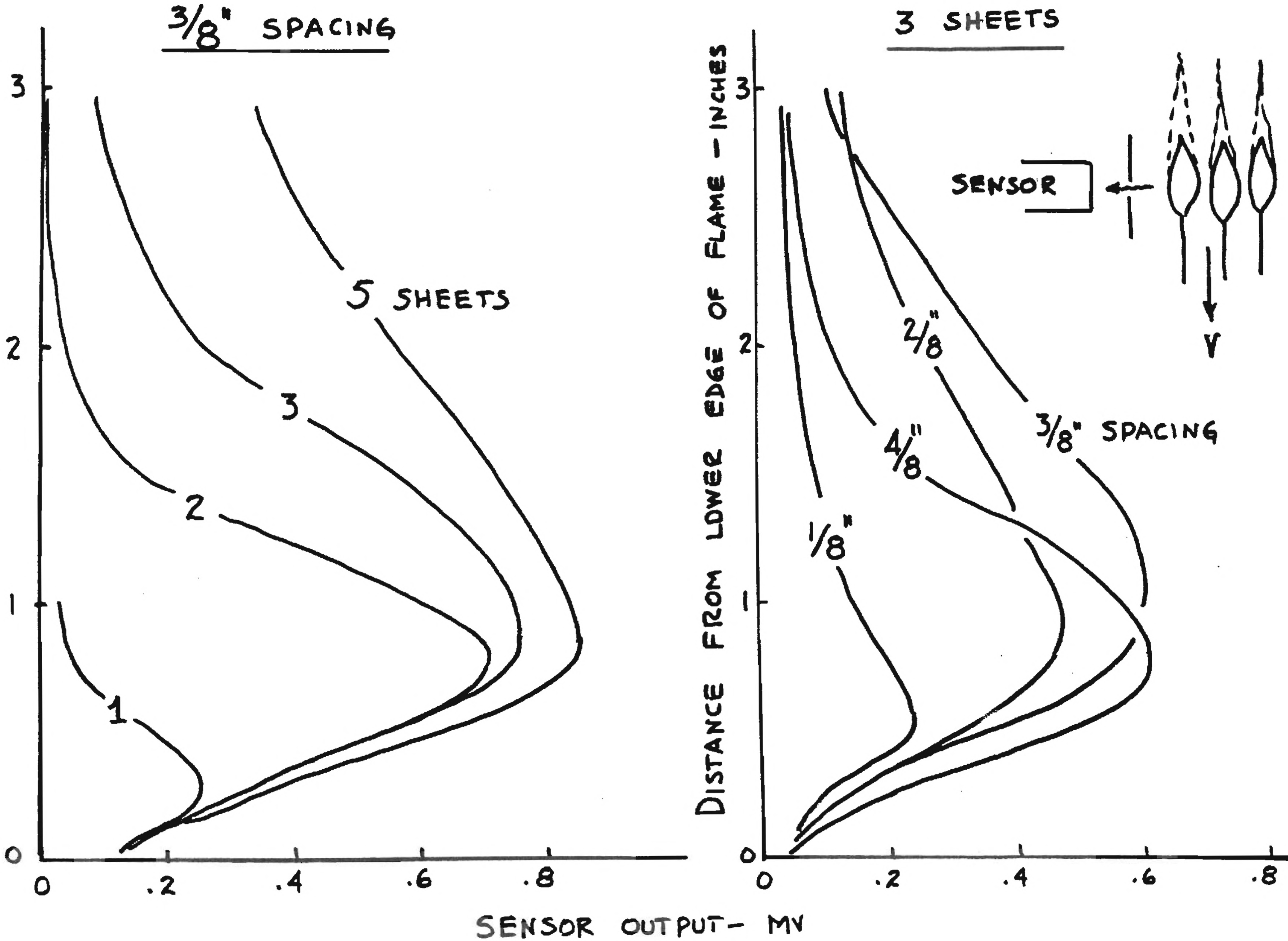
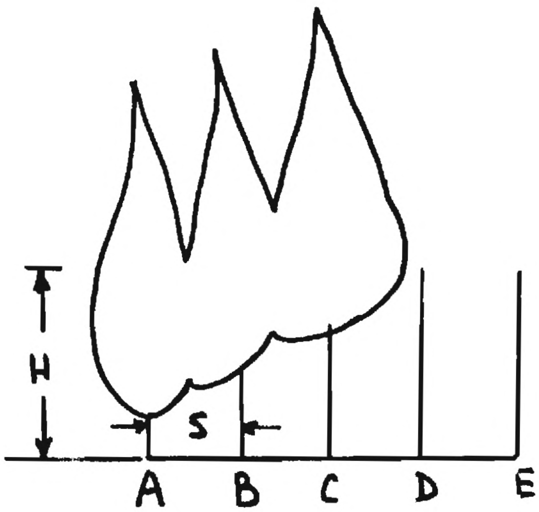

3/8" SPACING
5 SHEETS
3
2
1
3 SHEETS
SENSOR
V
2/8"
3/8" SPACING
4/8"
1/8"
DISTANCE FROM LOWER EDGE OF FLAME - INCHES
SENSOR OUTPUT - MV
0
.2
.4
.6
.8
1
2
3

FIG. 4

FIG. 5

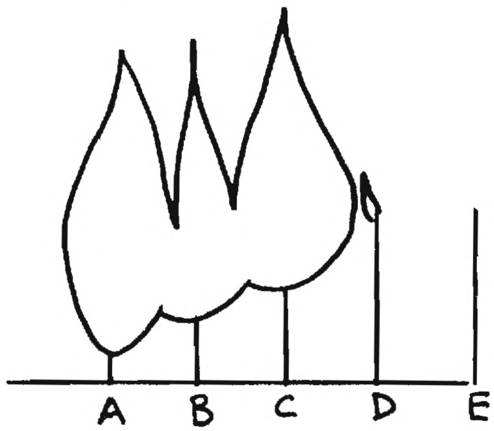


a)

Sheets A,B,C burning downward at uniform rate

Sheet D heating rapidly

Sheet E heating slowly by flame radiation



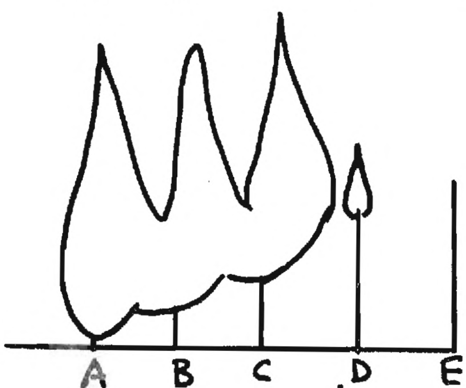
b)

Sheets A,B,C continue to burn

Flame appears on the back side of sheet D

Sheet E begins to heat more rapidly

Temperature of sheet E is T^*

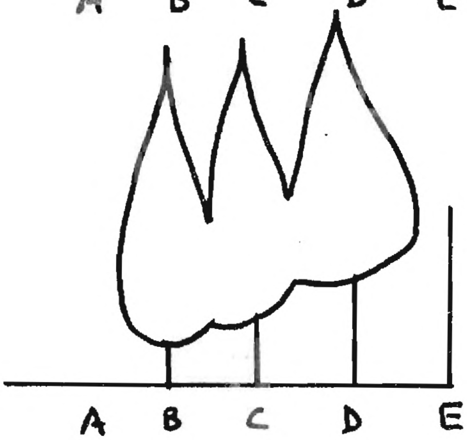


c)

Sheets A,B,C continue to burn

Flame climbs over the top of sheet D, and grow to full size quickly

Heating rate of sheet E begins to increase



d)

Sheet A burns out

Sheets B,C,D burning downward at uniform rate

Sheet E heating rapidly

N.S.F./RANN Conference on Fire Research
May 28, 29, 1974
Georgia Institute of Technology
Atlanta, Georgia

Guggenheim Laboratories
Princeton University
Princeton, New Jersey 08540

N.S.F. Grant No.
GI32554X1

A PROBLEM IN FIRE SAFETY:

FLAME SPREADING ACROSS LIQUID FUELS

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Mr. H. W. Mehtz - Undergraduate

Project Summary

Fundamental Studies of flame spreading across condensed phase combustible materials can contribute much to an understanding of many problems which society today considers important and unanswered. In particular, one can mention such problems as aircraft fuel fire safety, combustion techniques for removal of oil spills, fabric flammability, rapid combustion through stratified fuel/air mixtures (flash-over in home fires, mine safety, etc.). It is important to note that the understanding and techniques developed to study burning and flame spreading over liquid fuels (including determinations of radiation effects and induced gas phase flow fields) has far greater applicability than to liquid fires alone. The physical concepts and developed experimental techniques are also valuable to similar research on combustion and flame spreading over solid materials.

Theoretical work undertaken encompasses a complete analytical solution of the flame spreading phenomena over liquids in which both the gas and liquid phase flow fields are treated simultaneously. This approach permits one to obtain the flame spreading rate as an eigenvalue of the problem and to understand the relative importance of gas phase processes to the propagation mechanism.

The development and evaluation of the physical model upon which the theory is based is guided by experimental efforts which measure: 1) exact propagation velocities over the liquid surface, 2) the subsurface induced flow field parameters (temperature and velocity distributions), and 3)

the indirect gas phase flow field parameters. Thus the program also provides a diverse source of comparative information for the theoretical results. Indeed, the measurements of the liquid flow field parameters thus far suggest that the heat transfer model in the liquid (which is key to the flame propagation) may require some reconsideration in the proposed physical modelling.

Progress Report

A. Theoretical Investigations

It must be remembered that the flame spreading problem is an eigenvalue problem in that the spreading rate is unknown. In a frame of reference fixed to the flame, the spreading velocity would be a parameter in the upstream boundary condition; i.e., the liquid velocity at upstream infinity is the spreading velocity and therefore an eigenvalue of the problem. In any analytical treatment, we must have a mathematical procedure which will determine the eigenvalue as well as the reacting flow field solutions.

The flame spreading problem involves two phases (gas and liquid) which are both very important. The field equations in each phase are coupled through the interface conditions. The temperature-induced, surface-tension forces cause a reversal of the flow in both phases, thereby amplifying the nonlinearity of the problem. The only hope for a solution of the reacting, mixing flow equations rests upon a numerical integration. In particular, an alternating difference, implicit method has been chosen to solve the elliptic system.

The nondimensionalized equations for vorticity, stream function, temperature, and species concentrations have been written and a computer program has been developed and is being debugged. The program involves an iterative approach. At present, the solutions for vorticity and stream function are found by iteration for given temperature and species concentration fields. Once convergence for the fluid mechanical variables is obtained, the iteration on the thermochemical variables proceeds until the converged solutions for both fluid mechanical and thermochemical variables are obtained. So far convergent solutions for the fluid mechanical variables have been obtained and debugging of the thermochemical calculations is proceeding satisfactorily.

The fluid mechanical boundary conditions are not rigid for this natural convection problem. Rather than specifying the velocity at the boundaries or specifying that the normal derivative of the velocity is zero, we have specified a weak smoothness condition. In particular, the third normal derivative of the stream function is set to zero at the boundaries.

B. Experimental Investigations

Previously available experimental results do not provide the clear conceptual description of the sub-flash-temperature flame spread mechanism needed both in deriving and checking any analytical model. The principal effort of this part of the Princeton research program has been to provide a more detailed experimental description of the flame spreading process, particularly for the subsurface convective flow field and interface boundary conditions. The success of these endeavors has been strongly dependent on the extension and application of a little known method used to determine flow fields in electrolytic fluids. The developed hydrogen bubble flow visualization technique is capable of defining both vector magnitudes and directions of velocity in the subsurface liquid flow field generated beneath a spreading flame. Studies thus far have been conducted using a 45%

ethanol/water mixture as fuel. Flow field observations have been made over a range of initial bulk fuel temperatures (8-20°C) where transition from liquid phase to gas-phase controlled flame spreading occurs. In addition very small thermocouples (100_{μ}) were used to measure the temperature distribution in the flow field.

Figures 1 and 2 are examples of the sub-surface velocity and temperature field measurements obtained for an initial bulk temperature of 11.5°C (mean flame spread rate of 1.65 cm/sec). Measurements are described in a reference frame moving at the mean flame spreading rate. At a bulk temperature of 11.5°C (and at all bulk temperatures in the range 8-180°C), the flame actually spreads in a pulsating fashion[1,2]. However no unsteadiness is observed in the subsurface flow field.

It is most significant to note that the flow reversal region is much more complex than had been previously envisaged by our own group or numerically predicted by

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1) F. L. Dryer, H. J. Herring, A. Helmstetter, W. A. Sirignano and I. Glassman, "Flame Spreading Across Liquid Fuels, Aerospace and Mechanical Sciences Report No. 1140, Princeton University, November 1973.

2) Akita, K., "Some Problems of Flame Spread Along a Liquid Surface" Fourteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa. (1973).pp

Torrance[3]. The circulations suggest the existence of more than one eddy within the reversal region. The flow reversal region in the liquid phase together with that which must also exist in the gas phase appear to cause a surface temperature distribution which does not decrease monotonically with distance ahead of the flame. (A result which contrasts with the surface temperature distribution predicted by Torrance[3] or measured by Akita). There are a local minimum and maximum resulting in a temperature "valley" slightly preceding the flame front. This surface temperature distribution and the gas phase flow reversal region above it are believed to be strongly related to the pulsating character of flame spread at bulk temperatures below the fuel "flashpoint". Future experiments are planned to investigate this relationship and to describe the subsurface flow field for flame spread over fuels which produce significant radiation.

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3) Torrance K. E., "Subsurface Flows Preceding Flame Spread Over a Liquid Fuel", Comb. Sci. and Tech. 3, 133 (1970)

C. Accomplishments

a. Proof that flame propagation across liquids whose bulk temperature (T_B) is below the flash point (T_F) is controlled by convection within the liquids.

b. Concept and analytical verification that the convection is established by a surface tension gradient.

c. Verification that the relationship of the bulk temperature to the flash point temperature establishes the mechanism of flame propagation.

d. Emphasis of the anomaly of the flame propagation speed when $T_B > T_F$ and later independent proof that this large propagation speed is due to fuel stratification.

e. Concept that flame propagation (for $T_B < T_F$, liquids or solids) is a lean flammability limit problem.

f. Suggestion of a method for the combustion clean-up of oil spills.

g. Analytical determination of induced air flow by natural convection during flame propagation to show that forced convection opposing flame propagation must be high in order to reduce the spreading rate.

h. Definition of the role of radiation in flame propagation, particularly in small fires.

D. Applications

Fundamental studies of flame spreading across condensed phase combustible materials can contribute much to an understanding of many problems which are becoming of greater importance in today's world. One can mention such problems as aircraft fuel fire safety, combustion techniques to remove oil spills, fabric flammability, rapid combustion through stratified fuel/air mixtures over condensed media, (i.e.; flashover in home fires, flame spread over low flash-point fuels), etc. The relevance of these problems in terms of fire safety is increasing due to the larger volumes of fuels which must be transported to meet today's energy needs and the growing role which synthetic materials play in the garment and building industries.

E. Future Milestones

Theoretical

The next theoretical milestone will be the completion of the debugging of the portion of the computer program which involves the thermochemical calculations. At that point, the computer program should yield reliable results. These results would include general trends as well as specific flow field details. The dependence of the spreading rate on certain input parameters such as fuel properties, air temperature, and flame size could be determined.

A careful comparison between experimental and theoretical results would be made with the intention of explaining certain experimentally-observed phenomena such as the non-monotonic variation in surface temperature.

Experimental

Subsurface flow field measurements obtained thus far have provided new insight to the character of flame spread over liquid fuels. Indeed there is some evidence of several deficiencies in the conceptual description of the mechanism upon which previous theoretical efforts have been based. Further experimentation will be required to aid in evolution of the proper physical model of the flame spread mechanism, and in turn these results will provide a more complete source of comparison for analytical results.

A more precise hydrogen bubble tracking technique has recently been developed. Additional measurements of the sub-surface flow field for flame spread over ethanol water fuels will provide better definition of the reverse-flow region particularly in the vicinity of the flame front itself. This information is important to further development of a conceptual understanding of the pulsating flame spread phenomena. Sub-surface measurements will also be conducted on flame spread over fuels which have a larger radiation component to evaluate the possible modification of the surface temperature distribution (other experiments at Princeton have suggested that this is the primary mechanism through which radiation affects the flame spread rate).

A second major effort of the future research program will be to experimentally define the gas phase flow field in the vicinity of the spreading flame front. Available surface temperature data suggest the gas phase flow reversal region plays some part in energy transport across the flame front, and indeed may also play a major role in producing the pulsating character of the flame spread. Both the temperature and velocity distribution in this flow region will be studied. Finally other experimental efforts will attempt to elucidate the possible importance of convection, radiation, and gas phase conduction which occur during pool burning.

In summary, future experimental efforts will continue to support development of a clear physical understanding of the flame spread phenomena, provide experimental results for comparison with analytical calculation, and direct new efforts toward understanding of the steady combustion mechanism of pool fires.

Recent Reports And Publications

W. A. Sirignano, "A Critical Discussion of Theories of Flame Spread Across Solid and Liquid Fuels", Comb. Sci. and Tech., 6, 95 (1972).

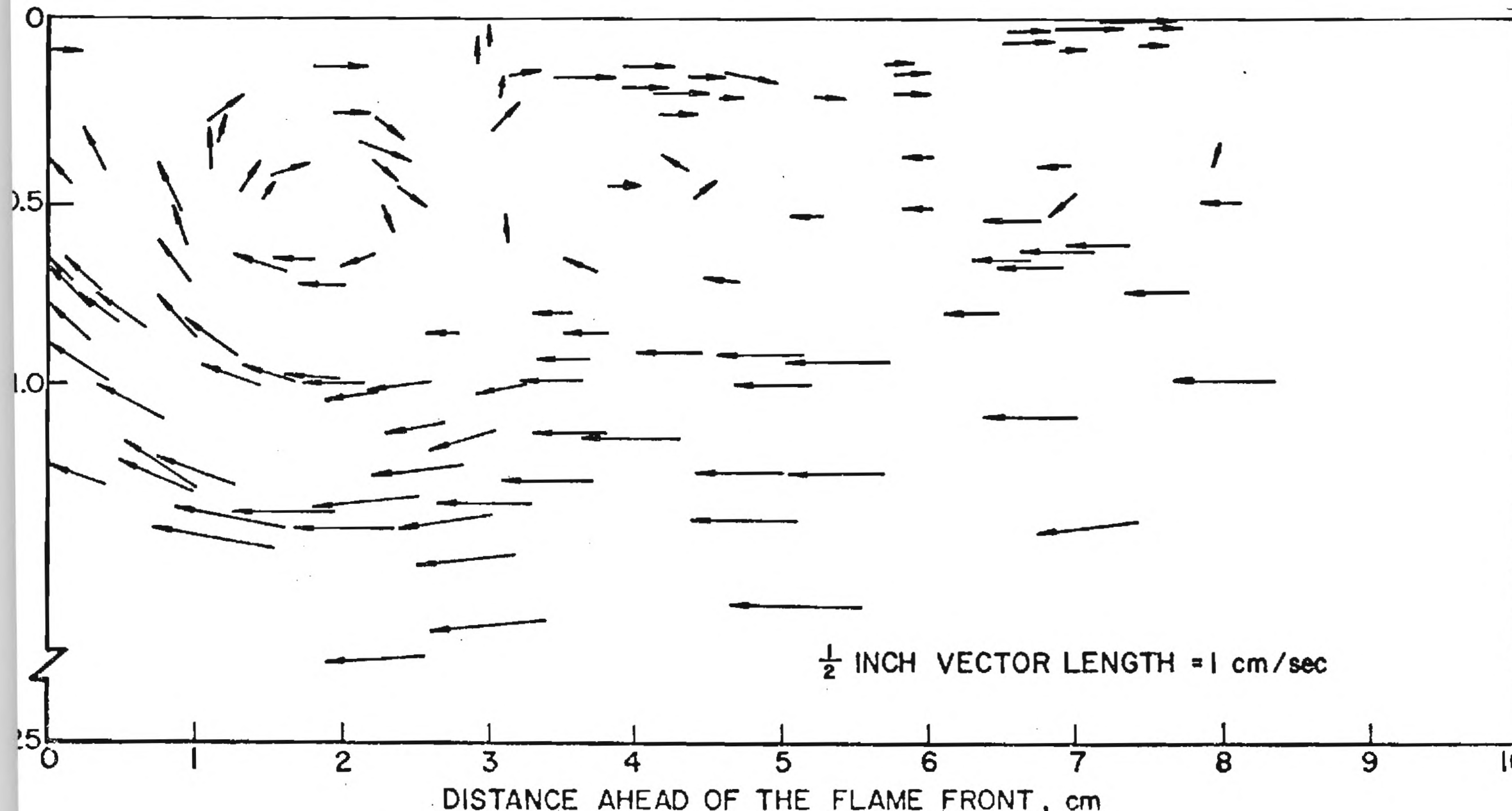
W. A. Sirignano, "Theory of Flame Spread Above Solids" accepted for Publication, Acta Astronautica, 1974.

F. L. Dryer, H. J. Herring, A. Helmstetter, W. A. Sirignano and I. Glassman, "Flame Spreading Across Liquid Fuels", Aerospace and Mechanical Sciences Report 1140, Princeton University, November 1973.

J. S. Westberg, "Combustion of Oil Slicks by Means of Solid Oxidizer", Bachelor of Science in Chemistry Undergraduate Thesis (1973).

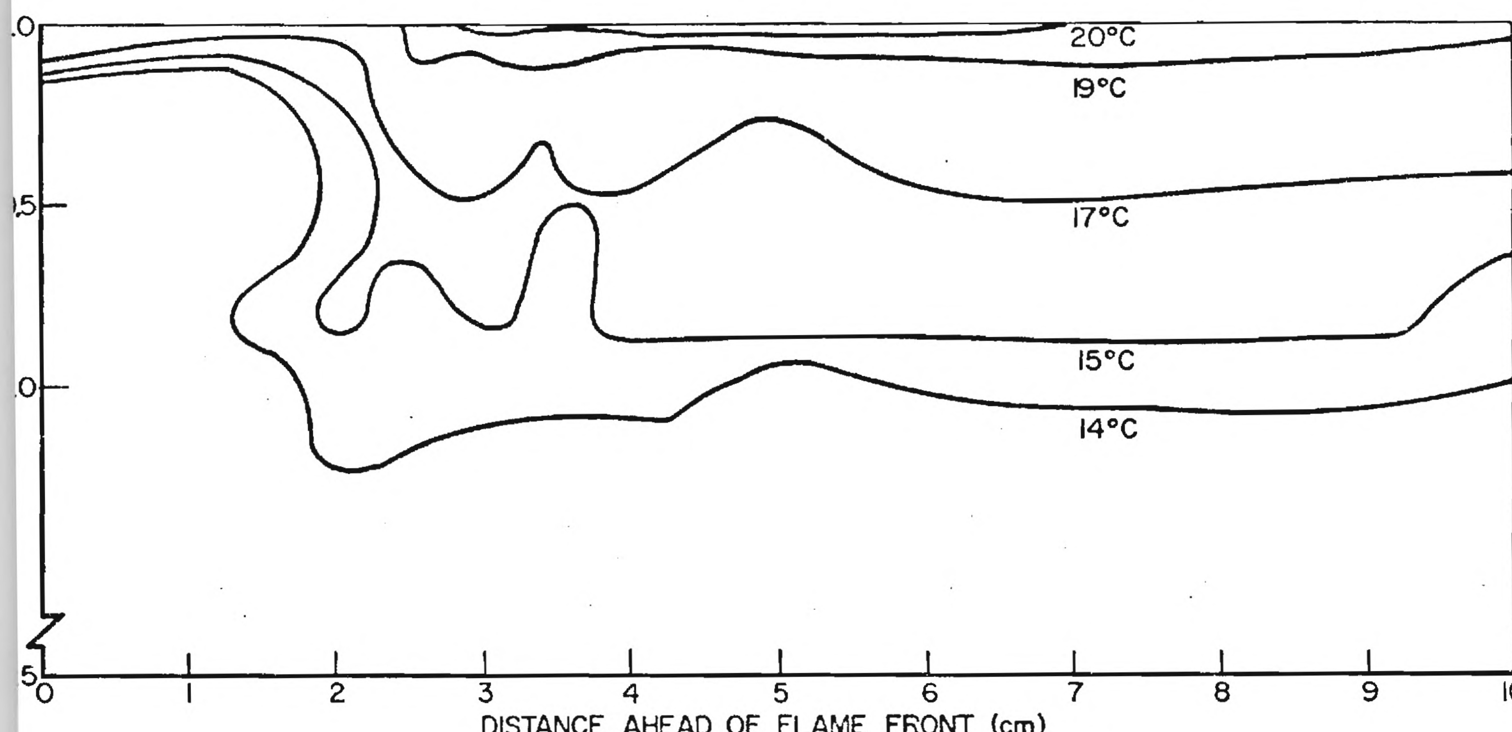
C. C. Feng, "Flame Propagation Through Fuel-Air Mixture Layers", Ph.D. Thesis, Aerospace and Mechanical Sciences Dept. October 1973.

A. J. Helmstetter, "An Experimental Study of Flame Spreading Over Liquid Fuels: The Sub-Surface Flow Field". M.S.E. Thesis, Department of Aerospace and Mechanical Sciences, 1974 (in preparation).



VELOCITY VECTOR FIELD IN SUBSURFACE LIQUID LAYER. FUEL: 45 PERCENT ETHANOL IN DISTILLED WATER. INITIAL BULK TEMPERATURE: 11.5°C FLAME SPEED = 1.65 cm/sec

Fig. 1



ISOTHERMS IN SUBSURFACE LAYER. FUEL = 45 PERCENT ETHANOL IN DISTILLED WATER. INITIAL BULK TEMPERATURE: 11.5°C FLAME SPEED = 1.65 cm/sec

Fig. 2

Institution: Cornell University NSF Grant: GI-31894X

Grant Title: FLAME SPREAD OVER LIQUID FUEL

Principal Investigator: Kenneth E. Torrance
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Cornell University
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(607)256-6253

CORNELL UNIVERSITY

Other Personnel: Martin Remorenko, Roop Mahajan, Joseph Shum.
Graduate Research Assistants.

Project Summary:

The objective of the research is to determine in a quantitative way the range of parameters which will allow a flame to spread over the surface of a liquid fuel when the fuel is at a temperature below its flash point. A theoretical study will be made of subsurface fuel movements induced by surface tension and buoyancy forces. Gas phase effects will be approximated by suitable boundary conditions on the free surface of the fuel. The analysis will be extended to couple the liquid fuel to a simple model of gas-phase flow above it, with mass transfer included. Stable and conserving finite-difference simulations of the governing equations will be employed. Such numerical procedures allow all important coupling mechanisms and physical processes to be included.

Progress Report:

Improved numerical methods have been developed for solving the time dependent, partial differential equations governing mass, momentum and energy conservation within a layer of liquid fuel. The layer is taken as two-dimensional with a hypothetical flame spreading over the surface.

The overall strategy of the liquid fuel parametric studies was to take two base cases, and to vary one parameter at a time away from values appropriate to a base case. The two base cases are representative of hydrocarbon fuels of shallow (0.4 cm) and deep (5 cm) depth. Using the foregoing strategy, a study of the effects of the five parameters appearing in the liquid phase model was undertaken and essentially completed.[1,2] Quantitative data was obtained by using a sequence of refined computing grids. The induced liquid movements were found to be functionally dependent on layer depth and linearly dependent on surface tension force. Certain details of the liquid motions were found to be essentially independent of Prandtl number, buoyancy, and the imposed flame speed.

Specific calculations were undertaken to permit comparison of calculated quantities such as eddy length, fuel surface temperature, and reverse surface velocities with reported data on hydrocarbon and alcohol fuels.[3] The apparent agreement is very good, although considerable effort is still required to confirm the agreement over a wider range of parameters.

The model has been extended to include surface evaporation and the gas-phase motion above the liquid surface. The balances of surface stress (viscous and surface tension), mass transfer (evaporation), and heat (sensible and latent) have been successfully added. Both finite-rate and Schvab-Zeldovich kinetic formulations for gas phase combustion are currently being developed.

Accomplishments:

1. Numerical models were developed for the liquid phase. New information on numerical modeling has emerged.

2. Effects of layer depth, flame speed, buoyancy, surface tension, and Prandtl number on the liquid fuel motions were documented.[1,2]

3. A comparison[3] with available experimental data reveals that induced surface velocities are in good agreement with observed spread rates, thus suggesting that the liquid responds to a moving flame as if it were a quasi-stationary heat source. The model provides a means for estimating spread rates based on physical properties of the fuel layer.

4. A study of the effect of net surface evaporation on the magnitude of the surface tension force suggests that net evaporation through the surface exerts no significant influence on surface tension.[4]

5. The development of a numerical model for coupled gas/liquid phases has been initiated and substantial progress achieved. The model has been successfully applied to an evaporating fuel surface without combustion.

Potential Applications:

The research is relevant to activities involving the use, handling, or production of flammable liquids, and will provide fundamental information on the physical mechanism of fire spread over liquids. Such information will be useful for the design and control of industrial combustion processes, and for the engineering design of storage facilties and fire prevention and extinguishment systems. The results are also relevant to the successful burning of oil or hydrocarbon spills.

Future Milestones:

Future work will include the development of a complete gas/liquid combustion model and a study of the effects of combustion parameters, flame unsteadiness, and flame radiation. More detailed comparisons with experimental data are anticipated.

Reports:

[1]Torrance, K. E. and Mahajan, R. L, 1974. "Surface Tension Flows Induced by a Moving Thermal Source", in review.

[2]Torrance, K. E., 1971. "Subsurface Flow Preceding Flame Spread Over a Liquid Fuel", Comb. Sci. Tech., 3, pp. 133-143.

[3]Torrance, K. E. and Mahajan, R. L., 1974. "Fire Spread Over Liquid Fuels: Liquid Phase Parameters", abstract accepted for presentation at XV Symposium (International) on Combustion.

[4]Mahajan, R. L. and Torrance, K. E., January 12, 1973. "Evaporation, Surface Kinetics, and Surface Tension Effects for Liquid Fuels", Report prepared under NSF Grant GI-31894X, Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York.

FIRE SAFETY IN URBAN HOUSING

University of California, Berkeley
Berkeley, California 94720

National Science Foundation
Grant Number GI-43

PROJECT SUMMARY, ACCOMPLISHMENTS, AND FUTURE PLANS

INTRODUCTION

There is a great need to establish a rational base for the design of buildings safe from fire. The research group at Berkeley has undertaken an interdisciplinary program of basic and applied research on building fires, fire safety, and fire-oriented design. Certain aspects of this program are sponsored by the Department of Housing and Urban Development through the NSF RANN office. This support is particularly valuable since it provides for specific channels of information exchange with an operating unit responsible for the fire safety of buildings.

As can be noted in the personnel list above, the Berkeley Fire Safety Group consists of faculty investigators from a number of different disciplines who have had a wide variety of experience in engineering and architecture. They have worked together in this project to achieve a variety of goals. Some of the applied goals of the project are to improve materials and structures from a fire safety viewpoint and to provide scientific and engineering input to the process of formulating codes, standards and other fire-related legislation.

The fire world has changed dramatically during the last few years and there are very alarming trends toward worse fire hazards in the future. In the past, the fire safety of the built environment has generally been improved by applying hindsight to problems that have caused tragic fires. Until recently, all these fires shared the common base of being fueled by cellulosic materials (usually in the form of paper, cotton and wood) and this has strongly influenced the *ad hoc* solutions to fire safety problems. Today we find that man-made polymers (i.e., plastics) have widespread application and the old solutions to fire safety do not always work when these materials are involved in the fire. This means that a rational base for the design of fire safe buildings must be founded on a fundamental knowledge of both cellulosic and plastic fueled fires. This has been one of the overall themes of the Berkeley Fire Research Group.

Another theme of the Berkeley Fire Research Group has been to restate the essential features of the traditional approaches to fire safety so that they might be better understood by the designers, code officials and materials suppliers and so that changes made necessary by the use of plastic materials could be readily incorporated in codes and standards. A list of distinct goals of fire safety in urban housing has been developed and this can serve as a framework to show how the diverse research projects conducted by the Berkeley Fire Research Group fit together. This list is formulated on the concept that there are a set of distinct goals of fire safety with overlapping means.

GOALS OF FIRE SAFETY IN URBAN HOUSING

1. Reduce risk of fire outbreak
2. Provide for safety of occupants in case of fire.
3. Reduce probable property damage and potential paths to conflagrations in case of fire.
4. Provide for safe and successful fire fighting.

The means to achieve these goals are the subject areas for specific research tasks undertaken by the Berkeley Fire Research Group. This group consists of faculty investigators from a number of different disciplines. The program is organized around five major topics:

1. System-oriented study of the overall building-fire process and human response (Industrial Engineering).

2. Combustion processes and fire spread in relation to materials and micro-level physical factors (Mechanical Engineering).
3. Fire response of structure, selection of materials, and design for minimum fire hazard (Civil Engineering).
4. Fire safety criteria and tests for single family living units (Civil Engineering).
5. The Architectural designers organization and possible solutions to fire hazards in buildings (Architecture).

The basic purpose of the research in the first four of the areas listed above is to provide better understanding of important physical, chemical and human factors which control ignition and growth of fires in structures. The fifth topic above is being undertaken by a portion of the fire research group devoted to developing the architectural approaches to rational fire safety design. Of all the professions involved in the design and construction of the urban environment, the architect is most responsible for those factors which affect the fire safety. There is a great need to translate the large body of scientific fire research information into terms which architects can use. Thus the architectural aspects of the fire project at Berkeley are organized into research topics that feed the architectural design process. A study of the relation of morphology of building types to fire safety has been undertaken. Another research effort is to simulate the performance of elevator systems under fire conditions. Finally, the most important aspect of the architectural research is the search for better ways to utilize the kind of information developed in the engineering part of the project in the architectural design process.

The principal papers and reports are listed at the back of this summary. These are available to anyone wishing to learn of the specific findings of any of the projects. A list of the specific tasks is as follows:

Engineering Approaches

Development of a design-oriented computable simulation of the total building-fire process

Field study of the unwanted building-fire process

Analysis and experimental study of human response to fire situations

Fire radiation

Flame spread analyses with application to enclosed fires

Polymer combustion and inhibitor mechanisms

Prediction of structural response to fire

Heat transfer in standard fire endurance test

Quantitative analysis of combustible assemblies

Development of new fire safety criteria and fire tests for single family living units

Tests and criteria for smoke and toxic gases produced in burning single family living units

Architectural Approaches

A systems approach to fire problems

A morphology of building types in relation to fire safety

Simulation of elevator system performance in fire conditions

Social and behavioral factors

Environmental control systems

Continuous review of research priorities, coordination and application of new information

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Lars Lerup, Assistant Professor, Department of Architecture, Wurster Hall

J. P. Protzen, Assistant Professor, Department of Architecture, Wurster Hall

Publications

Babrauskas, Vytenis, "Fire Safety Criteria and Tests for Dwellings - Post-flash-over," presented at the C.I.B., W.14 Commission Meeting, Braunsweig, Germany, April 1974.

Bazjanac, Vladimir, "Towards a New Breed of Simulation Models in Architectural Design," PROC. OF THE DESIGN ACTIVITY CONF., London, 1973.

Bazjanac, Vladimir, "Elevators in Evacuation of High Rise Buildings," PROGRESSIVE ARCHITECTURE, April 1974, pp. 88-89.

Bazjanac, Vladimir, "Berkeley-Novi Put u Naslavi Arhitekture," COVJEK I PROSTOR, Yugoslovia, November 1973.

Bazjanac, Vladimir, "Architectural Design Theory: Models of the Design Process" invited paper for the PROCEEDINGS OF THE SYMPOSIUM ON BASIC QUESTIONS OF THE DESIGN THEORY, Columbia University, May 1974.

Bazjanac, Vladimir, "The Promises and the Disappointments of Computer aided Design," PROMISES AND DISAPPOINTMENTS OF COMPUTERS IN ARCHITECTURE, Editor, Nicholas Negroponti, Auerbach Press (in press)

Becker, James, Bizri, Hani, and Bresler, Boris, "FIRES-T A Computer Program for the FIre REsponse of Structures - Thermal," Fire Research Group Report #FRG UCB 74-1, Department of Civil Engineering, University of California, January 1974.

Bender, Richard, "Industrialized Building (Housing is a Red Herring)," URBAN HOUSING, PROC. OF THE INTN'L CONF., Editor Vasily Kouskoul, Wayne State University May 1973, pp. 186-192.

Bender, Richard, "Fire Safety in Urban Housing: A Report of the Work of the Architecture Experiment Laboratory," presented at the Conference of Fire Safety in Buildings Research-Practice-Needs, Airlie House, Virginia, July 1973.

Bizri, H., STRUCTURAL CAPACITY OF REINFORCED CONCRETE COLUMNS SUBJECTED TO FIRE INDUCED THERMAL GRADIENTS, Ph.D. Dissertation, University of California, Berkeley, 1972.

Bresler, B. and Bizri, H., "Reinforced Concrete Column Response to Fire," Discussion No. 9, Fire and Blast Committee, ASCE-IABSE International Conference on Planning and Design of Tall Buildings, Preprints Vol. DS, 1972.

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ABSTRACT

May 22, 1974

HARVARD UNIVERSITY

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Institution

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Grant Title

The Home Fire Project

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HU: Visiting Profs. - Neville Fowkes, Joseph Prahl, Patrick Pagni
Res. Fellows (part time) - Charles Knight, Kun Min, Tom Shen
Research Associate - Richard Land
Grad Students - Franco Tamanini, David Evans, Manny Ratafia, Peter Greene

Project Summary

To make predictable the Growth of Fire in a Home.

Progress Report
Attached

Accomplishments, Potential Applications, Future Milestones

The many small pieces of this project are each making progress. The calculation of fire convections in the spirit of hydraulics seems possible in spite of the complex geometries. The required overall quantitative description of pyrolysis and burning of cellulose and plastics still seems far off. Extinguishment unless purely empirical, requires a knowledge of the burning mechanism and hence progress has been greatest for a burning vertical surface and less for the system problem (crib) and the detailed mechanism (extinguishment of a charcoal block). The attempt to model fires with acceptable precision requires great care with the modeling of radiation. The exact nature of the difficulty and its possible cure is now under study. Measurement of radiation from fires has shown some simple relations for small laminar flames and is now being tested on larger turbulent flames.

The full scale bedroom test was encouraging for many of the above small projects by showing reasonable interrelations between data even though the full fire event is not yet calculable. The rate of value destruction in a home by fire can be estimated only cruddly in mechanistic terms. For a statistical approach, the available data is sparce indeed but an approach is being attempted through a cooperative appraiser.

The real meaning of "room flammability" and "fire safety in a home" depends upon a knowledge of the response of a room to fire and the sensitivity of that response to changes of geometry and material. To test the reproducibility and hence meaning of a full scale fire we propose a total of 3 full scale bedroom fire tests each fully instrumented and each profiting by the experiences of the previous ones. The second one will occur this summer.

Reports

"A Study of the Extinguishment of Wood Fires," F. Tamanini, Ph.D. thesis, Harvard Univ., 1974.

"Natural Convective Flow Through an Opening," H. Emmons, project report in preparation.

"The Large Scale Bedroom Fire," Paul Croce, project report in preparation.

"Thermal Degradation and Spontaneous Ignition of Paper Sheets in Air by Irradiation," Ubhayakar Shivadev and Howard Emmons, Combustion and Flame, Vol 22, pp. 223-236, 1974.

"Radiative Energy Transfer from Gaseous Diffusion Flames," G. Markstein, to be presented at 15th Int. Symposium on Combustion, Tokyo, 1974.

The Rate of Fire Spread on a Bed. P. Pagni

The rate of fire growth in a bedroom-like enclosure is being studied with emphasis on early burning initiated in bedding materials. Preliminary experiments indicate a strong influence of sheets and mattress covers on overall growth. For the case of a polyurethane mattress core, the fire expands from a point of ignition into a cylindrical configuration as it spreads. Models predicting flame spread rates through bedding materials are being developed.

Extinguishment of Wood Charcoal Fire by Water. D. Evans

The purpose of this investigation is to determine in some detail the effects on the combustion of wood charcoal due to water impinging on the burning surface. Recent work has been directed towards measurement and prediction of the burning rate, with no water application, from a surface reaction theory.

Wood charcoal cylinders, 2.6 cm. in diameter and approximately 10 cm. long are burned from one end in an axisymmetric stagnation flow of room air. A steady state combustion is obtained by automatically advancing the sample at the regression rate of the burning surface, thereby maintaining the flat burning surface in the stagnation region. By varying the main stream velocity the surface temperature and burning rate can be altered. Main steam velocity is varied in the range of 15 m/sec to 40 m/sec, the lower limit being determined by an inability to maintain steady combustion.

Typical results can be characterized by a main stream velocity of 30 m/sec which produces a burning rate of 9×10^{-4} g/cm sec, with an average surface temperature of 925°C for a charcoal density of 0.28 g/cm^3. The internal temperature distribution appears to decrease nearly linearly at a rate of 90°C/mm for the first 6 to 8 mm from the burning surface and then decays exponentially to room temperature. Measurements of the density profile within the burnt sample by H.W. Emmons indicate a surface density only 10% lower than the bulk value with significant deviations only within the first 6mm.

Since a small percentage of the mass is consumed below the surface, a surface reaction theory alone seems justified for prediction of the burning rate. At present this surface reaction theory is being built upon available graphite kinetics (Strickland-Constable), CO and CO_2 formation at the surface, and heat and mass transfer properties measured in a separate experiment.

Heat and mass transfer rates in a stagnation flow, as a function of main stream velocity, were obtained by measuring the evaporation rate of water from a porous plate of the same diameter as the wood charcoal cylinders used. The results can be summarized as

$$Nu = 6.79(RePr)^{.3}$$

$$Sh = 1.78(ReSc)^{.4}$$

for mainstream velocities in the range of 10 m/sec to 40 m/sec, and ΔT (mainstream-surface) approximately 10°C with all properties evaluated at the film temperature.

Fire Pyrolysis of Cellulose. K. Min

Pyrolysis of cellulose is being studied by heating filter paper samples in an inert gas stream, mixing the "cracked" gaseous pyrolysis products with excess air and passing the mixture over a heated platinum element. The thermal response of the platinum element is a measure of the relative heat of combustion of the gaseous pyrolysis products as they are produced. From this response, the overall kinetic constants for the pyrolysis reaction can be deduced.[1]

Currently, this technique is being developed for improved reproducibility with the aim of using it to investigate the effect of condensation of gaseous pyrolysis products on the apparent kinetic constants in situations where migration and condensation of the gaseous products could be significant.

[1] McCarter, R.J. "Apparatus for Rate Studies of Vapor Producing Reactions" NBS Spec. Publ. 338 (1970).

Optical Survey of Paper Ingition. P. Greene

This is a preliminary study, aimed at establishing the mode of ignition of sheet filter paper when subjected to infra-red radiation. (Filter paper was selected because of its chemical simplicity relative to that of ordinary paper.) Optical techniques used so far include direct observation of the flame with a video-tape system and indirect observation of density gradients in the plume with a Schlieren shadowgraph. The rather faint Schlieren pictures were also recorded on video-tape by using an extra-sensitive phototube (the "Tivicon") in a standard Sony video camera; the framing rate of the video system was 30 frames per second.

Questions which we hope to answer by this survey are

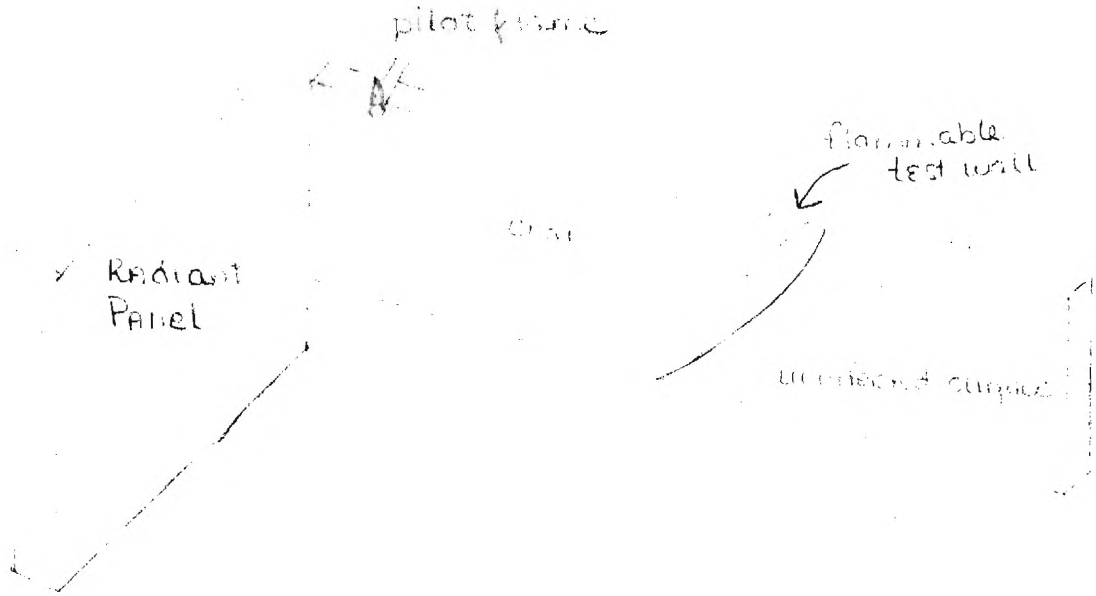
1) Where in space does the flame originate?
2) How does the flame propagate?
3) What role does a crack in the paper play? (Preliminary evidence suggests that a crack is a necessary, but not sufficient, condition for the occurrence of a flame.)

Still photographs we have made display two apparently different modes of ignition; Case I appears to be a volume flame which occurs everywhere in the plume at once, whereas Case II is a flame which originates at the crack edge, and then propagates up the plume.

Radiatively Enhanced Flame Spread Over a Vertical Surface. M. Ratafia

Research has been initiated on the spread of flame over a vertical surface which is being nonuniformly bathed in thermal radiation. The configuration being considered, which is shown below, has been chosen because

a) it is directly applicable to the understanding of home fires,
b) it is essentially the same as that employed in some existing standard flammability tests, and
c) it is sufficiently simple so as to be analytically tractable.



Convection in an Enclosure. C. Knight

We are attempting to gain a detailed understanding of fluid flow mechanisms important in an enclosure with and without openings. Two approaches have been adopted: numerical studies of laminar natural convection in 2-D planar and cylindrical geometries and a quasi-1-D theory of ceiling-jet flow with openings below ceiling level, backed by hydraulic flow experiments.

Thus far the numerical studies have concentrated on the closed planar configuration. The formulation is in terms of vorticity and stream function, the Boussinesq approximation is made, and the numerical treatment employs an implicit alternating-direction scheme, first order upwind differencing, and fast Fourier transform techniques. A Prandtl number of 0.73 and σ = source width/room width = 1/16 have been used in all cases, and generally Grashof Number = 4×10^8 (near laminar stability limit).

The primary studies to date have the heat source on the floor and may be summarized as follows:

A. Centrally located source with $\mathcal{R} = 0.5, 1, 2, 3$. The starting plume and subsequent flow development is what one would expect.[1] At later times there is a strong horizontal stratification for $\mathcal{R} \geq 2$, but for smaller $\mathcal{R}$ there is distortion due to persistence of starting vortices in the upper corners. The steady state flow pattern involves a plume, ceiling jets, wall jets, and floor jets with an essentially potential core region.

B. Source halfway between the center and left wall with $\mathcal{R} = 1.5$. With an isothermal left wall the flow development is similar to that in A. There is a slight Coanda effect bending the plume to the left wall, but this tendency is counteracted by the strongly stable stratification of the fluid to the left. With an adiabatic left wall the stabilizing effect is not present, and the plume is collapsed into the left wall. These studies make fairly clear the relevance of heat transfer mechanisms on flow characteristics.

C. Source in lower left corner with $\mathcal{R} = 1.5$. The cold isothermal left wall causes the thermal boundary layer (plume) to separate. This occurs early in the transient rise of hot gases, and ultimately in steady-state there is a massive separation with the plume leaving the wall one third of the way up.

Our next step in the numerical studies will be extending the treatment to allow openings. Another means of understanding convective flows in rooms is by hydraulic analogy, which is in an early stage of development.

[1]Chapter 6, J.S. Turner, Bouyancy Effects in Fluids.

Corridor Ventilation. T. Shen

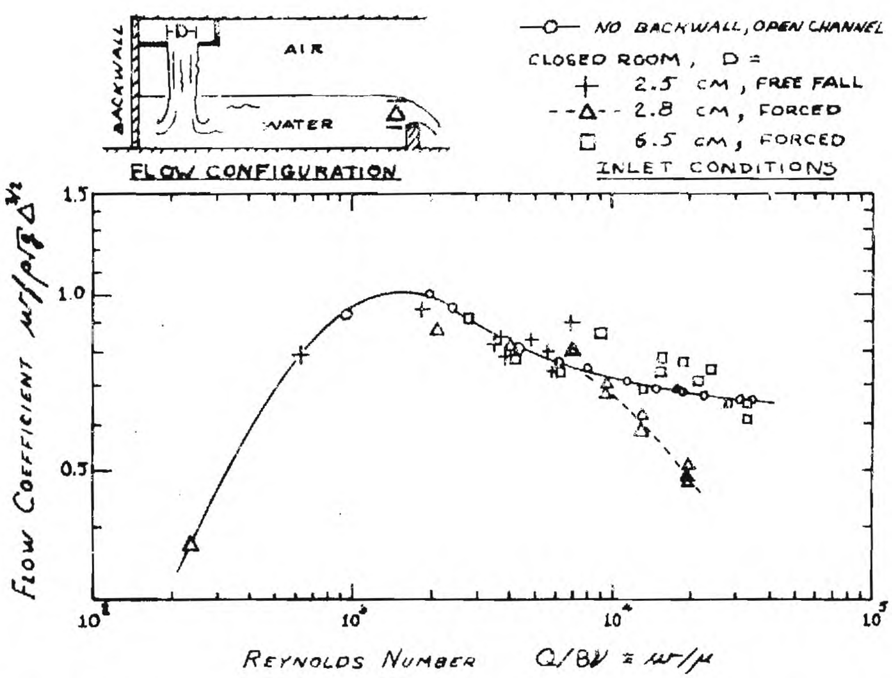
Experimental apparatus consisting of a corridor with partially open end permits us to test flow with Re up to 30,000. Vertical temperature profiles at exit, gas inlet temperatures and inlet gas flow rate were measured. Results were plotted as flow coefficient c_f versus Re for various corridor exit heights. A preliminary study of the experimental results indicated that the gas flow is well stratified at low Re. The inlet momentum of the gas flow plays more and more important role in controlling the flow movement at exit as Re gets larger and larger. As Re increases to about 20,000 - 30,000 and inlet gas temperature remains at about 100°C or more, it appears that the inlet momentum of the gas flow completely controls the gas movement at the corridor exit.

Hydraulic Modeling of Gas Flows Exiting from a Burning Enclosure. J. Prahl

The exit flow of the products of combustion of a localized fire in an enclosure is modeled as a buoyancy driven flow by introducing water in the presence of air to an inverted version of the enclosure. The water, falling from the origin of the fire to the ceiling, fills the room to a level sufficient to drive the mass flow from doorways or windows in the enclosure. The scale size of the model is chosen to preserve the Grashof number based on the properties of water and the density difference between water and air.

Measurements taken on a model of the full-scale bedroom fire yield a doorway flow coefficient, based on hydraulic theory, that varies between 0.35 and 1.0 over an exit Reynolds number range of 240 to 35,000 and remains reasonably constant at about 0.68 over Re 10,000 to 35,000. The flow coefficient is mildly sensitive to inflow conditions when the initial inflow velocity exceeds that dictated by the Grashof number. Thus, the area of the modeled fire was increased for increasing flow rate so that the initial water velocity remained insignificant compared to the velocity attained in free fall through the scaled room dimension (i.e. Grashof number similitude).

Further experiments are planned with salt water, in the presence of pure water, to determine the influence on the exit flow coefficient, of entrainment, of pure water by the entering salt solution, thereby modeling the fire's oxygen demand. It is expected that the only noticeable effect on the flow coefficient will occur at the high exit Reynolds numbers when substantial choking of the doorway by the exit flow inhibits the inflow of pure water through the doorway and forces a significant change in the enclosure pressure.



FLOW COEFFICIENT VS. REYNOLDS NUMBER FOR VARYING INLET CONDITIONS
MODEL BEDROOM FIRE SCALE – 0.056

A Study of the Extinguishment of Wood Fires. F. Tamanini

The experimental part of the study consists of extinguishment tests by application of water sprays to vertical wood slabs and wood cribs in self-sustained combustion. The results for the slabs are correlated using parameters derived through a trial and error procedure. As a conclusion, a corrected form $\dot{m}_w''*$ of the water application rate ($\dot{m}_w''$) is suggested by the data as a more significant parameter than the water application rate itself. This correction is given by the experssion

$$\dot{m}_w''* = \dot{m}_w'' \frac{\dot{m}_{f_1 max}''}{\dot{m}_{f_1 be}''}$$

where $\dot{m}_{f_1 max}''$ is the maximum burning rate of the structure without extinguishment

and $\dot{m}_{f_1 be}''$ is the burning rate at the beginning of extinguishment.

The time required for extinguishment and the mass lost during extinguishment turn out to be proportional to the -n power of $\dot{m}_w''*$, with n=1.5 - 1.75. This result is valid for both geometries investigated (slabs and cribs). In the case of slabs and for the type of spray used in the study, corrected water application rates below .19-.24 x 10^{-3} gm/cm^{2}sec are practically ineffective at arresting the combustion before complete burn out. The value of this critical rate of water application is affected, in the case of cribs, by the orientation of the spray and the porosity of the crib.

A conceptually simple thermal model can adequately predict the results of the experiments with slabs. In particular, numerical solution of the equations shows that corrected water application rates greater than .8-1.0 x 10^{-3} gm/cm^{2}sec bring about significant soaking of liquid water in the charcoal layer during extinguishment. This conclusion is interpreted as indicating the upper limit of the efficient use of water as the extinguishing agent of the self-sustained combustion of wood. No theory is as yet available for the case of more complicated fuel arrays (cribs). The similarity in the trends shown by the experiments with slabs and cribs gives hope that a more general theory can be based on similar ideas.

As a first step in the direction of the suppression of burning in confined spaces, the case of the combustion of cribs with cooling of the gases in the vertical shafts is also considered. A decrease in burning rate up to 30% of the undisturbed burning rate is brought about by the vaporization of water in the shafts. This measured quantity cannot be predicted by a modified version of an available theory of crib burning, probably because of difficulties with the measurement of the rate of vaporization of water, used as an input to the theory.

Fan Measurement of Fire Gas Velocities. R. Land

Development of a small anemometer for measurement of fluid flows, particularly in the hostile environment of fires continues. A small lightweight fan on a needle shaft is held in simple bearings and is optically sensed. Fan sizes range from 0.5 cm to 3.0 cm dia. and the biggest fans on a shaft weigh less than a gram. In the full scale bedroom fire test (July 1973) two fan anemometers 1.5 cm dia. gave readings of air flow near the ceiling and near the top of the door jam. The record failed after several minutes for reasons that have not been determined but are presumed to be condensation of tar on the bearings. Both fans resumed operation during flashover. Further development work has been delayed while an industrial producer is sought. Two manufacturers are currently considering the information we have supplied.[1] Numerous inquiries about the availability of the fan anemometer have had to await clarification of this solicitation.

Calibration techniques have been refined and confidence in measurements throughout the low flow region from threshold of the device, 15 to 30 cm/sec in air, to 10 m/sec can be obtained. A hot air jet is also available to extend readings from room temperature to 400°C. The linear calibration of fluid speed vs fan speed appears to depend upon the fan size, pitch angle of the blades, and fluid used, essentially a Reynolds number and pitch angle dependence. While these fans appear similar to the Briam type anemometers which are an order of magnitude larger, the theory of Ower does not seem to apply fully.[2] The basic principles of these devices continue to be investigated.

[1] Flow Technology, Inc., Phoenix, Ariz. markets a superficially similar device at surprisingly high prices.

[2] Ower & Pankhurst, The Measurement of Air Flow, Pergamon, 1966, p. 204 ff.

The Rate of Value Destruction of a Home by Fire. N. Fowkes, H. Emmons

The investigation is proceeding simultaneously along statistical and deterministic lines.

<u>The Statistical Approach</u>. Ideally what is needed is fairly detailed and extensive data on fire spread, smoke movement and extinguishment needs; together with cost estimates associated with the resulting damage. Appropriately detailed fire spread data has not been uncovered (and should if possible be collected in the future). Fire cost data no doubt exists, but so far the attempts to obtain the data have failed. Possible data leads are being pursued; however the outlook is not good. Under the circumstances an attempt will be made to collect spread and cost data in a particular home fire case.

The Deterministic Approach. Generally it is believed that it will be necessary to understand the fire processes in order to predict destruction costs with any accuracy. With this is mind the following particular question associated with the fire spread problem is under investigation. "What gas motions are produced by a heat and gas source located at a particular position in a building, under a variety of ventilation conditions?" This work together with the combustion and pyrolyses work undertaken elsewhere in the project, should lead to quantitative results on fire spread in a house. The cost estimate results will then be combined with the fire spread results to produce estimates of destruction costs.

The drawings of a 50 year old two story wooden house to be used for our trial fire estimates have been made and a reasonable selection of modest furnishings have been selected. The house is estimated to be worth \$30,000 in the present market and the furnishings come to \$13,000 by Sears Roebuck Catalogue.

The Natural Convective Flow Through an Opening. H. Emmons

A general treatment, in the spirit of hydraulics, of the flow of hot gases out of a window or door has been developed. It is applicable at all stages in the growth of a fire and can be applied for flow between two rooms as well as to the atmosphere. Like all such theories it must be supplemented by measured flow coefficients to account for the vena centracta and viscous effects properly.

An application to the data of the full scale test was encouraging. A project report is in preparation.

Radiative Energy Transfer from Gaseous Diffusion Flames. G. Markstein

This work forms the initial part of a continuing study, with the ultimate goal of obtaining relatively simple relationships for estimating the radiative energy transfer from fires with acceptable accuracy. This task requires data obtained by systematic variation of the optical thickness of the fire. To meet this objective, an array of a number of flames arranged along the radiation path is used.

In the first phase of the study radiative emission and absorption measurements on an array of ten laminar diffusion flames have been performed, using gaseous hydrocarbon fuels selected to provide a wide range of tendency for soot formation. With the narrow-view-angle radiometer sensing the regions of highest radiative intensity of the flames, the following results were obtained:

1) With the highly sooty flames of propylene, isobutylene and 1,3-butadiene, the transmittance τ_n and radiance N_n of n flames satisfied the "grey-gas" relationships $\tau_n=\exp(-an)$, $N_n=N_1[1-\exp(-an)]/[1-\exp(-a)]=N_\infty\alpha_n$, where $N_\infty=N_1/[1-\exp(-a)]$ is the asymptotic optically-thick limit of radiance, and $\alpha_n=1-\tau_n$ the absorptance of n flames.

2) With the less sooty flames of aliphatic fuels and of ethylene, the data could be represented as a linear superposition of two weighted grey-gas terms, $\tau_n=A\exp(-an)+(1-A)\exp(-bn)$, and the corresponding expression for N_n. The numerical results obtained by least-square fits are presented in the following table.

FUEL	N_1 W/cm² sr	A	a	b	$N_\infty a$ W/cm² sr	$N_\infty b$ W/cm² sr	N_∞ W/cm² sr
CH_4	.1561	.6448	.02049	.2949	7.70	.611	5.18
C_2H_6	.2917	.7864	.02030	.3211	14.51	1.062	11.64
C_3H_8	.4782	.9269	.04228	.5295	11.55	1.163	10.79
n-C_4H_{10}	.5615	.8494	.03997	.2937	14.33	2.206	12.50
iso-C_4H_{10}	.5896	.9276	.05336	.5253	11.35	1.443	10.63
C_2H_4	.6230	.9456	.03786	.4294	16.77	1.785	15.95
C_3H_6	.6540	1.000	.07643	—	8.89	—	8.89
iso-C_4H_8	.6610	1.000	.09755	—	7.11	—	7.11
1,3-C_4H_6	.8006	1.000	.14420	—	5.96	—	5.96

These results and their interpretation are further discussed in ref. 1. The work is currently continuing with an apparatus of considerably increased scale, using an array of turbulent gaseous-fuel diffusion flames.

[1] Markstein, G. H., paper to be presented at the 15th International Symposium on Combustion, Tokyo, August, 1974; also FMRC Report in preparation.

Pressure Modeling of Building Fires. **R. Alpert**

In the past year, about 200 fire experiments have been performed in the 2.1 cubic meter pressure vessel at up to 40 atm. The first series employed a geometry involving a square polymethyl methacrylate pool in a ventilated enclosure with ceiling height 1.56 times the pool width. Peak burning rate (Sherwood number) correlated with Grashof number for two enclosure sizes and pressures from 10 to 40 atm. Burning rates were 20 to 50% higher than for the same pools in the vessel without an enclosure. However, comparison with atmospheric-pressure behavior in a scaled enclosure four feet high showed that under these conditions a different behavior occurred; burning rate increased to a peak about five times as high as the rate with no ceiling. This flashover-like behavior is probably caused by a radiative flux from the ceiling and upper walls to the polymer pool. This flux, based on the measured ceiling temperature, is a significant fraction of the total heat input to the fuel at one atm, whereas at elevated pressures burning rate per unit area increases as $P^{2/3}$ while ceiling temperature and radiant flux from the ceiling remain constant.

In subsequent experiments, other geometries were selected to permit investigation of the effects of radiation on pressure modeling. One series of tests was performed with flame propagating up vertical ducts of polymethyl methacrylate with h/d ratios from 3 to 15. The burning rates, expressed as Sherwood number, vs. $P^{4/3}t$, where t is time, correlated one atm and 8 atm data at the same Grashof number, for two h/d values, confirming the modeling theory for this geometry.

Future studies will deal with parallel vertical fuel surfaces with variable separation and height. Ultimately this geometry may be burned in an enclosure to help define the role of wall radiation in modeling. As a preliminary to parallel walls, tests are now being done with single walls. Flame spread rate up a wall, which accelerates as the flame advances, has been measured for a 15 cm high wall at 18 atm, and agrees with one-atm data for a 150 cm wall, when plotted as $P^{-2/3} \cdot V$ vs. $P^{2/3}X$, as required by modeling theory (V is spread rate at position X, measured from bottom).

Atmospheric Pressure Modeling of Building Fires. P. Croce, G. Heskestad

The hypothesis[1] for an approximate scaling scheme is based upon the observation that the normalized burning rate of wood cribs in a free-burn situation can be expressed as a function of a single parameter, P, the "crib porosity" of the structure. For a crib burning within a vented enclosure, the combustion relative to free-burn, it is claimed, will depend primarily upon differences in fluid mechanical properties and composition of the gas feeding the fire. Accordingly, the ratio of burning rate in an enclosure to free burning rate is expected to be a function of relevant geometric parameters, collectively expressed as G, for both the crib and the enclosure and enclosure ventilation parameters in addition to the crib porosity, P. Quantities such as temperature, gas specie concentrations, smoke obscuration and normalized radiant energy are expected to be sensitive to the same parameters as well as the location of measurement.

The experimental plan involved the burning of various crib structures in three enclosure sizes. The crib plan included a "standard" crib and others with variations in porosity only, gross geometry only (crib height) and in crib structure with P and G held constant. The enclosure plan included geometrically similar (H:W:L=1:1:1.5), vented enclosures at full, half and quarter scale (H=8, 4, 2 ft). Full width, horizontal openings centered on the end walls served as vents. In addition, the enclosure walls were thermally scaled for proper thermal response.

Some of the data obtained to date are shown in Figure 1a.-d. plotted against the ratio of ventilation parameter, $Ah^{1/2}$ (A = vent area, h = vent height) to unconfined burning rate, Rr. This ratio is a governing parameter according to the hypothesis. The data presented are the burning rate ratio, gas temperature increase, wall temperature increase and oxygen concentration. Other data collected but not presented herein include additional gas and wall temperature measurements at different locations, the concentrations of carbon dioxide, carbon monoxide and total hydrocarbons, smoke obscuration (optical density/length), and a radiation measurement looking into the vent. All of the data in Figure 1 are quasi-steady values in that they have been averaged over the interval during which the crib mass decreases from 80 to 30 percent of original crib mass. These data are encouraging in that good agreement is demonstrated for tests done at different scale sizes under similar conditions of h/H.

Future planned work consists of developing the hypothesis in terms of generalized dimensionless quantities, studying reradiation and transient effects, and broadening the experimental work to include more realistic fuel and vent geometries and measurements of fire spread to discontiguous fuel elements.

[1] G. Heskestad, "Modeling of Enclosure Fires," 14th Symposium (International) on Combustion, The Combustion Institute, 1973.

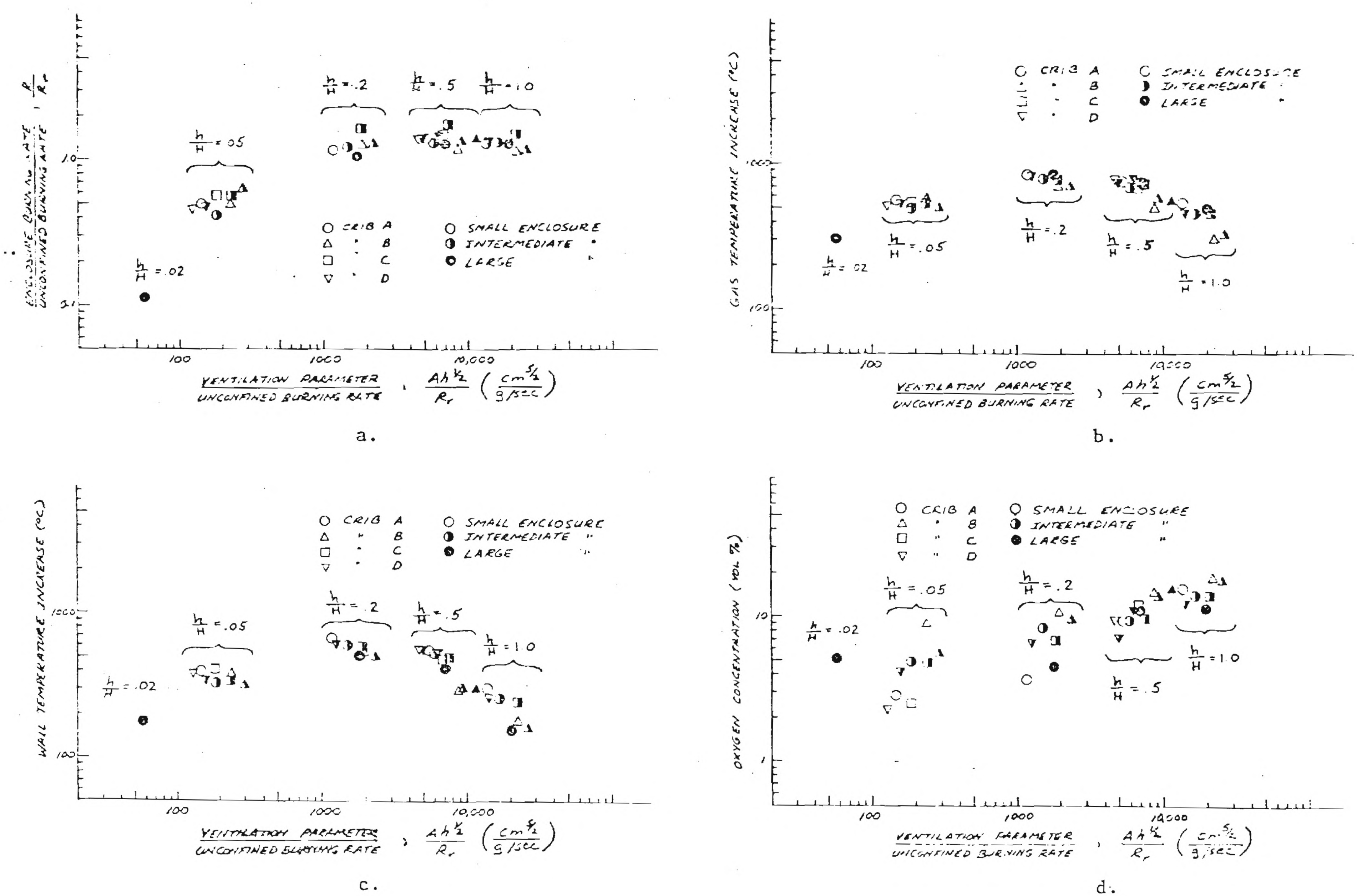


Figure 1. Plots of burning rate ratio, gas temperature increase, wall temperature increase and oxygen concentration vs. the ratio of ventilation parameter to unconfined burning rate.

Large-Scale Testing. P. Croce, G. Heskestad

The purpose for conducting a realistic large-scale test is to provide an opportunity for making related measurements and observations under realistic home fire conditions to all task workers, and, hence, to provide realistic information and direction to all task efforts. The goal is to observe fire spread to, and including, the flashover phenomenon.

An 8'x12'x8' high bedroom (furnished with bed, bureau, desk and chair, carpet, curtains, bookshelf, clothes and TV) was selected as the test facility. The fuel load for the test was 4 pounds per square foot of floor area. Windows were simulated (curtains only) and the door was open during the test to provide ventilation.

Instrumentation was provided to monitor continuously the following quantities: gas temperatures at 34 locations, ceiling temperatures at 6 locations, floor temperatures at 4 locations, wall (or other solid surface) temperatures at 17 locations, heat flux at 5 locations, O_2 concentration at 3 locations, CO_2, CO and THC concentrations at 1 location, smoke optical density at 3 locations, gas flows at 8 locations and radiative flux at 1 location.

The fire developed as follows: After a simulated match ignition on the mattress, flames grew gradually and steadily to approximately the eight minute mark, subsided gradually to approximately the fifteen minute mark, then grew rapidly to flashover (17:35 after ignition), after which the fire was extinguished. This behavior was reflected in all data channels as well as in an energy balance for the enclosure.

At approximately the eight minute mark, several reported or hypothesized "criteria for flashover" were satisfied, but flashover did not occur then. These criteria include paper ignition, minimum heat flux and flame involvement on the ceiling. In addition, it was estimated that the radiative feedback from the ceiling above the bed to the burning mattress at that same time should have been sufficient to expect significant enhancement of flame spread and burning rates. Possible explanations as to why flashover did not occur at that time include: i) the unavailability of fuels with relatively low heat capacity per unit area (such as curtains, which had fallen to the floor early in the test), ii) the shielding of radiative feedback from hot walls and ceiling by the relatively cool, bottom portion of a dense black smoke layer, and iii) the relatively low accumulation of unburned vapors prior to that time.

The test also demonstrated the usefulness of two newly developed flow measuring instruments. both of which performed satisfactorily under fire conditions. The first is a bidirectional, differential pressure flow probe with equal sensitivity in both directions and relative insensitivity to flow direction; the second is a low bearing-friction fan anemometer equipped with an optical readout system and remote electronics.

A second test, utilizing a duplicate facility with more extensive instrumentation, is planned for July 1974.

THE JOHNS HOPKINS UNIVERSITY

Institution

The Johns Hopkins University/Applied Physics Laboratory

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Fire Problems Research and Synthesis

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P. Schweda (State of Maryland Medical Examiner's Office)
V. Caplan (State of Maryland Medical Examiner's Office)
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STUDY OF FIRE DEATHS IN MARYLAND

Cooperating Laboratories:

School of Hygiene and Public Health/The Johns Hopkins University

Medical Examiner's Office, The State of Maryland

Project Summary

The objective of the Fire Fatalities Study, carried out during the past two years by the Applied Physics Laboratory in cooperation with The Johns Hopkins University School of Hygiene and Public Health, and the Medical Examiner's Office, Baltimore, is to obtain reliable and in-depth information about people dying as a result of fires. It involves case studies of the causes of fatal fires and of the biomedical consequences of fire exposure. Approximately 1/3 of the fire fatalities in the State of Maryland have been included. The study is restricted to casualties that occur at the fireground within 6 hours of the fire and does not include fatalities from fire-caused pulmonary complications, burn injuries, or other consequences.

The functional operation of the program can be divided into the following categories:

(1) Field Investigations
(2) Autopsies
(3) Laboratory Analyses
(4) Data Reduction
(5) Data Analysis and Synthesis
(6) Report Generation
(7) Program Coordination

Figure 1 shows the functional and organizational interaction of the various organizations and people involved in the program.

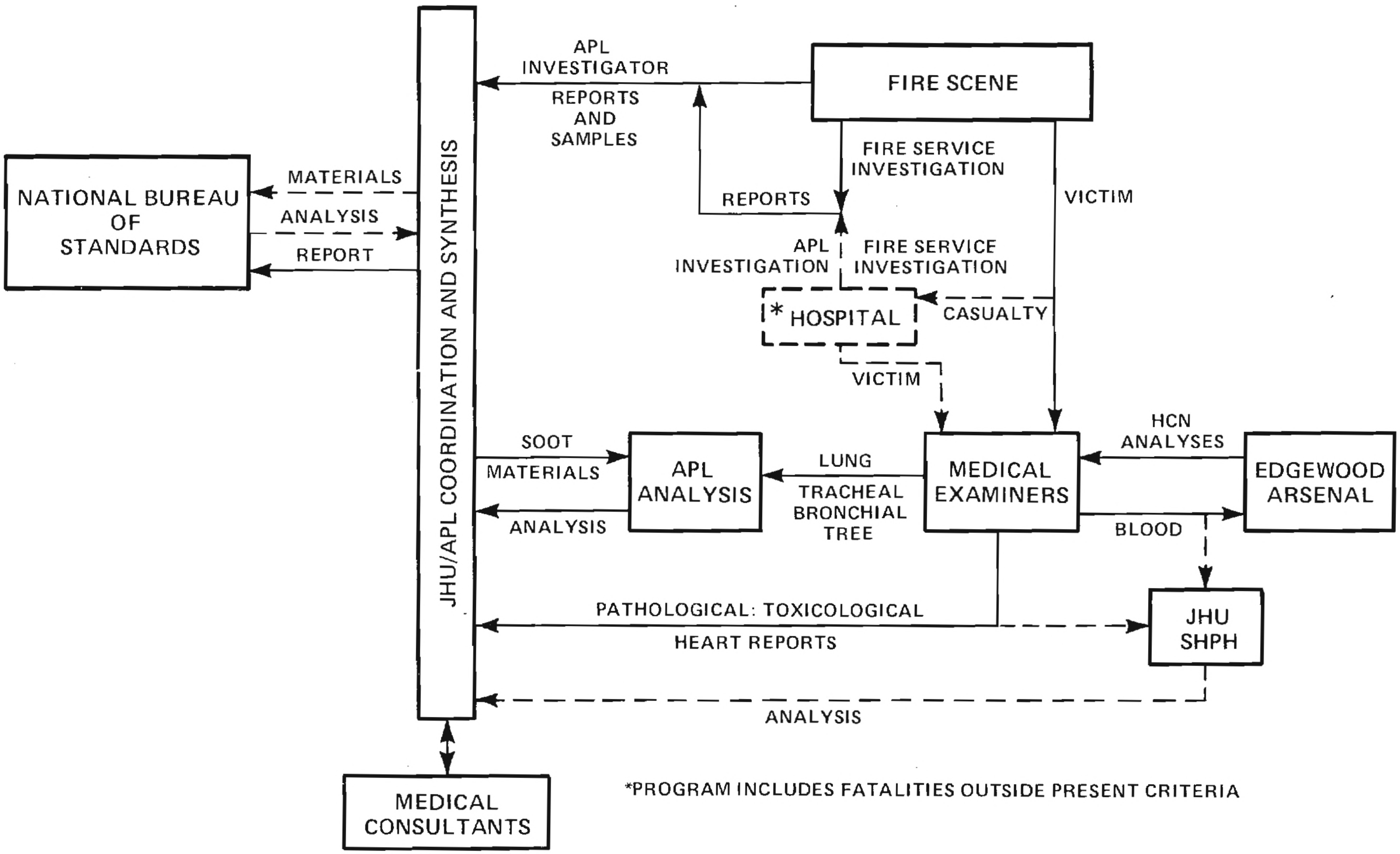

Fig. 1 FIRE FATALITY ORGANIZATION AND FUNCTION DIAGRAM

Progress Report*

One hundred seven fatalities have been investigated from 85 fires from September 1971 through January 1974. To be included in this series, *the case had to have died at the fire and had an autopsy by the Medical Examiner's Office, with carboxyhemoglobin measured in the School of Hygiene laboratory.* In addition, other post-mortem chemical measurements including blood methemoglobin and alcohol have been done, and all cases have had detailed evaluation of the coronary circulation at autopsy. A thorough review of the circumstances at the fire scene has been carried out. This is of critical importance in evaluating the cause of death. The cases have been primarily from Baltimore City and Baltimore, Anne Arundel, and Prince George's Counties. We estimate that 1/3 of all fire fatalities that have occurred in Maryland in this time period are included.

Although the data presented in this report include one hundred seven fatalities, data are available on one hundred forty fatalities through the same time period. The case studies used for this report were those for which a carboxyhemoglobin measurement was made by the School of Hygiene laboratory and all supportive data were available. The total data base through April 1974 is one hundred sixty-five.

There were 85 separate fires represented, with 15 fires where 2 cases died, 2 fires with 3 fatalities; and 1 with 4 fatalities. Fifty-five percent were caused by smoking and 11% were caused by children playing with matches. There was a preponderance of fatal fires at night, in contrast to the distribution of fire calls in general, which peak in the late afternoon around 5 p.m.

Approximately half of the cases were 40 years of age or older, and nearly one-fourth were children under the age of 10. Thus the principal victims at fires are children and older adults.

Table 4 shows the factors contributing to the deaths of the 107 cases. The large number of cases with coronary vascular disease present at the time of the fire is especially striking. Of these cases dying at the fire, carbon monoxide alone can account for the death in 48; in most cases carboxyhemoglobin (COHb) was greater than 65%. A blood COHb of over 65% is considered to be nearly always lethal due to depression of respiration and the circulation. Between 50 and 65% COHb, death has been known to occur, and some of the cases with blood COHb were in this range. High blood alcohol was also present with liver disease as a contributory factor in several of these cases with COHb between 50 and 65%.

*Based on lecture presented at International Symposium on Physiological and Toxicological Aspects of Combustion Products (The University of Utah) March 18-20, 1974, by Edward P. Radford, Byron M. Halpin, Russell Fisher, Paul Schweda, Yale Caplan, Bruce Pitt.

It is evident from Table 1 that carbon monoxide was a major contributor to death. Eighty-nine cases had blood COHb over 20%, and in 35 of these cases the combination of CO and coronary vascular diseases was sufficient to account for sudden death. Thus a second major contributing factor to death in this group was the presence of preexisting cardiovascular disease.

Analysis of the data indicates that for the groups with more than 20% COHb, the incidence and severity of coronary vascular disease was inversely related to the level of COHb reached. The observation is consistent with the high blood COHb and coronary vascular disease together leading to death in 35 cases. The terminal COHb is mainly a function of the depth and duration of breathing, and a high blood COHb at death requires that the cardiopulmonary system continue to function until that concentration was reached. Those cases with lower blood COHb had cessation of either respiration of circulation with less absorption of CO. Ventricular fibrillation from acute myocardial hypoxia induced by a rapid rise of COHb in individuals with a restricted coronary circulation is a highly likely explanation of a lower terminal blood COHb the more severe was the preexisting coronary vascular disease. The possibility that other pyrolysis products may have also contributed to ventricular fibrillation in the coronary cases cannot be ruled out, but one may conclude that unless their concentrations were comparable to CO in the fire, and their mode of action potentially as rapid as CO, they are unlikely to affect the myocardium more rapidly or severely than CO.

Another factor of importance in this series is the extent of body surface burned. Of the 107 cases, 72 had moderate or severe skin burning (50% or more of surface burned), but only in 18 cases is the burn the cause of death, and in 18 other cases burns could have contributed to death. Inflammation of the respiratory tract was present in a few cases, especially in cases where clothing was the principal material burned.

Burns alone appear to be a relatively infrequent cause of death in cases that die at the fire. It is significant that 32 of 72 cases with COHb over 50% had mild or no burns of the body surface. The inference is that if these people had not been overcome by carbon monoxide they could have escaped death in the fire. This point riases the question of why the victims did not escape. One case was a fireman who died of an acute myocardial infarction associated with severe coronary vascular disease immediately after leaving a smoky fire. He had 6% COHb, which may have been contributory, although the major cause was vascular disease. Two cases died of clothing fires outdoors. With these exceptions, all the cases that died at the fire either never escaped or were overcome after entering the burning building.

Table 2 shows an analysis of these cases in terms of blood COHb and blood alcohol. Of the 79 cases over age 18, 53 cases (67%) had COHb greater than 40%, an amount consistent with loss of sensorimotor function leading to collapse. In addition, 28 cases had blood alcohol above 0.15 gm/100 ml (0.15%), considered to be at or above the intoxication level for most individuals, with ataxia, slow reaction time, and impaired judgment. The highest alcohol was 0.39% in 2 males, 29 and 45 years old. An additional 14 cases had blood alcohol between 0.05% and 0.15% or a level which, taken with a high blood carboxyhemoglobin, also probably contributed to the loss of neuromuscular function. Of this group of 79 cases, most had enough absorption of CO to impair their ability to escape, but alcohol ingested prior to the fire also played an important part in 28. A similar pattern is present in the group of 9 cases with COHb between 20 and 40%. Five of these cases had alcohol above 0.15%, and the combination of alcohol and CO can account for loss of neuromuscular function and impaired judgment.

Most of the fire victims made some attempt to escape, and Table 7 summarizes the results of an analysis of why the victims did not escape from the fires. In four cases it was not possible to determine whether an attempt to escape was made, but in the rest of the cases nearly two-thirds showed evidence of having made escape attempts, or had reentered the fire for rescue or other purposes.

In Table 3, it is clear that carbon monoxide, with or without previous ingestion of alcohol, accounts for the failure to escape in more than 60% of the cases. Many of the infants (age 4 or less) that were killed, also died of CO inhalation. In many fires the victim was found at some distance from the burned material, and thus if instructions on how to avoid CO exposure had been followed, these victims need not have died.

In summary, four factors have been identified as contributing to deaths of individuals who die at the fire itself. Of these factors two relate to conditions existing prior to the start of the fire. First is alcohol ingestion, a well-known problem in fire victims. Excessive consumption may be related to the cause of the fire as well as why the victim does not escape. Blood alcohol was over 0.15% in 28 (35%) of 79 cases over the age of 17. Second, and less well appreciated, is moderate to severe coronary vascular disease, found to be present in 33 (45%) of 73 cases over age 20. This preexisting disease is particularly important when carbon monoxide may be inhaled. CO interferes with oxygen delivery to the heart and in these individuals their inability to compensate by increasing blood flow may suffice to cause ventricular fibrillation and rapid death.

Two other factors resulting from the fire are also of major importance as causes of death. First, of course, is extensive burning of the body, including in some cases the upper airway, but of the 107 cases dying at the fire, only two-thirds were moderately or extensively burned. In general we consider most of the burns to be secondary, in many cases occurring after death. The location of the body in relation to the origin of the fire is the principal basis of this conclusion. The final factor is carbon monoxide, present in significant amounts in the blood and definitely or probably contributing to the death in 84% of the cases dying at the fire. Clearly carbon monoxide exposure is a major problem in fires, and many cases die with no other cause present (unburned, found dead remote from the fire).

The contribution of smoke or other pyrolysis products to death or acute symptoms cannot easily be assessed from post-mortem examinations alone. Most of the 107 cases had obviously inhaled smoke, and evidence of pulmonary edema was present in a few of the cases. Soot was usually present in the trachea and bronchi, and often there was inflammation of the respiratory tract. In many of the 18 cases designated as burn deaths (Table 4), there is a definite likelihood that inhalation of smoke or other fire products was an important factor in causing the death of these individuals although whether glottal spasm or laryngospasm was involved is not obvious from the post-mortem results. Despite the importance of carbon monoxide as a lethal factor in fires, these other fire products are also important, especially in casualties surviving the fire. It is clear that in some of our cases acute effects of smoke products on the respiratory tract was significant.

Accomplishments

The work done up to now has revealed a number of interesting conclusions: Most of the fatalities have been consequences of fire accidents in dwellings. Transportation-caused fatalities and industrial accidents have been minimal. No major multiple disasters (above 4) have occurred in the period of investigation. Most of the fatalities were single incidents. Fatalities occur especially among children and older adults. Smoking by adults and playing with matches by children are the most frequent causes of fatal fires, and account for almost 2/3 of the 85 fires. Carbon monoxide intoxication, with or without preexisting coronary vascular disease was the principal cause of death in almost 80% of cases. Although burns, including burns or other factors leading to inflammation of the respiratory tract, may have contributed to death in about 1/3 of the cases, in only 16% were burns the primary cause of death. Our studies cannot yet define whether other gaseous products such as HCN are important in fire casualties, but it is evident that carbon monoxide is the principal intoxicant, especially for adults with preexisting coronary vascular disease.

Potential Applications

Knowledge of the physical and medical causes of fire deaths points out the direction for designs of "fire safe" house furnishings as well as the need for more intense public education and effective warning devices.

Future Milestones

The number of cases obtained previously has been limited to approximately 50 fatalities per year. The limiting factors are:

(1) The criterion that the fatality must be autopsied, and that death must have occurred within 6 hours of the fire incident.

(2) The Maryland State Medical Examiner has not up to now insisted on an intensive compliance by the Field Deputy Examiners in Maryland.

The size of the fatality study involving autopsies can be increased to approximately 100-125 cases per year in the following manner:

(1) The Maryland State Medical Examiner is willing to extend the number of autopsies by requesting maximum cooperation from the Deputy Medical Examiners. He estimates that an additional 30-40 cases per year can be made available.

(2) The Medical Examiner, Washington, D.C., has agreed, in principle, to be a collaborator in the fatality program. Approximately 35 cases would meet the criteria of the study.

By expanding the number of cases to what is an operational upper limit and by extending the chemical, biochemical and biomedical investigations beyond the present limits we expect to complete the study in a rapid fashion. The increase in the number of analyzed cases would provide a more secure statistical base for the relatively large number of diverse fire incidence causes for which there is now only sparse information. It will also allow identification of uncommon fatality causes.

It may be possible to include within this study a limited follow-up of fire victims that survive the fire incident by more than 6 hours. While these cases do not come under the direct jurisdiction of the State Medical Examiner it should, nevertheless, be possible to correlate fireground information (especially the chemical analysis of soot), with the medical histories of the fire casualties.

The complete chemical investigation of fire casualties currently involves the determination of carbon monoxide, ethyl alcohol, drugs and hydrogen cyanide in blood; volatile organic vapors and metal oxides in the lung; volatile organic vapors, metal oxides and hydrochloric acid in the soot deposits.

Reports

(1) Edward P. Radford, Byron M. Halpin, Russell Fisher, P. Schweda, Yale Caplan, Bruce Pitt, "Study of Fire Deaths in Maryland", to be published in Proceedings of International Symposium on Physiological and Toxicological Aspects of Combustion (The University of Utah), March 18-20, 1974, The Committee on Fire Research, National Research Council, National Academy of Sciences.

TABLE 1
CARBON MONOXIDE AND CORONARY
VASCULAR DISEASE AS
CAUSES OF DEATH
107 FIRE FATALITIES

CAUSE	NUMBER	PERCENT
CO ALONE	48	45%
CO + CORONARY DISEASE	35	33%
CO + BURN	5	5%
CORONARY DISEASE ALONE	2	2%
BURN ALONE	15	14%
UNCERTAIN	2	2%

TABLE 2
CARBOXYHEMOGLOBIN AND BLOOD ALCOHOL
CASES AGE 18 AND OVER

BLOOD ALCOHOL gm/100ml	COHB% > 40	COHB% 20-40	COHB% < 20	TOTAL	%
NONE	22	3	10	35	(44%)
< 0.05	0	1	1	2	(3%)
0.05-0.15	13	0	1	14	(18%)
0.16-0.25	11	4	4	19	(24%)
> 0.25	7	1	1	9	(11%)
	53	9	17	79	(100%)
CASES UNDER AGE 18 (NO ALCOHOL PRESENT)	23	2	3	28	
TOTAL ALL CASES	76	11	20	107	

TABLE 3
FACTORS RESPONSIBLE FOR
FAILURE TO ESCAPE FROM FIRES

REASON FOR FAILURE TO ESCAPE	ATTEMPT TO ESCAPE			TOTAL	%
	YES	NO	UNDETERMINED		
CARBON MONOXIDE ALONE	23	6	3	32	29.9%
CARBON MONOXIDE + ALCOHOL	31	6	0	37	34.6%
ALCOHOL ALONE	3	0	0	3	2.8%
BURN (INCL. RESPIRATORY)	5	0	0	5	4.7%
CORONARY OCCLUSION	2	1	0	3	2.8%
INFANT	1	12	0	13	12.1%
INVALID	1	3	0	4	3.7%
EXPLOSION	0	3	0	3	2.8%
CLOTHING FIRES (GENERALLY SUICIDES)	2	3	0	5	4.7%
SUICIDE	0	1	0	1	0.9%
CAR ACCIDENT	0	0	1	1	0.9%
	68	35	4	107	
	(63.6%)	(32.7%)	(3.7%)		

EDUCATION AND INFORMATION IN THE FIRE SERVICE

Project Summary

The objective of the program is to pursue a number of related projects whose purpose is to support the educational needs of people and organizations concerned with Fire Prevention and Control. This includes the advanced training of Fire Officers, of other fire-suppression oriented groups, such as Fire Science instructors in colleges, Fire Service instructors and of fire research or fire design groups. It is concerned with the education of the general public in fire-related matters.

In the absence of a focal point (such as the projected United States Fire Academy within the National Bureau of Fire Safety) several APL programs are being pursued that deal with specific problems, such as:

(1) Fire Safety Films

(2) Seminars and Workshops on "The Teaching of the Fire Sciences"

(3) Symposia and Colloquia in selected technical areas (Fireground Command, Control, and Communications; Fire Fighting Foams; etc.)

(4) Surveys on "Advances in the Fire Sciences"

(5) Bibliographic Materials

  a. Directory of Workers in the Fire Field

  b. Fire Sciences Dictionary and Source Book

(6) Development of a Fire Information System

Progress Report and Accomplishments

(1) Fire Safety Films

With the cooperation of the Montgomery County (Maryland) Fire Marshal's Office, and the Walter Johnson High School Film Group, a film ("Don't Get Burned") on general fire safety matters as seen through the eyes of students has been produced. This film has been widely circulated (Fire Marshals Association, Institute for Burn Medicine, National Safety Council, etc.) and is being handled by the National Fire Protection Association for general distribution (see Appendix I for comments).

A second film with concern for fire safety in inner city situations is currently being planned jointly with the Baltimore City Fire Department and the Southern High School of Baltimore.

While designed primarily for fire protection education of high-school students, the films are likely to be used by many citizen groups and organizations concerned with fire safety (National Safety Council, Consumer Products Safety Commission, Citizens Association, Boy Scouts, etc.).

(2) Seminars and Workshops on "The Teaching of the Fire Sciences"

The phenomenal rapid growth of courses in the Fire Sciences in Community Colleges and several Universities in the past five years has given rise to problems in the interchange of ideas regarding objectives, course content, accreditation and profession organization. Two national symposia have been held (March 1, 2, 3, 1973 and April 27, 28, 1974) one at APL, the other at the Northern Virginia Community College. The meetings were concerned with the academic aspects of fire protection instruction and with the professional problems encountered in teaching college level fire-related courses (Appendix II). The following questions were discussed:

What are the principal teaching objectives in the Fire Sciences?
What courses are offered and on what level of sophistication?
What are the course standards and requirements?
What innovative teaching methods are available?
What teaching materials are available?
Where do Fire Science students come from and what are their career opportunities?
What credit transfer problems exist?
How are Fire Science teachers selected and trained?
What organizations are needed to support the needs of Fire Science instructors?

The consensus at the end of the second conference was that an organization representing Fire Science or Fire Technology instructors should be established whose concerns include the following topics: information exchange, performance standards; model curricula, teaching aids development; student career counseling; grants solicitation. The lead toward this goal is to be taken by the Organizing Committee.

(3) Symposia and Colloquia Series

Over a period of years a number of technical colloquia have been made available without charge as audio and videotape recordings and widely distributed.

A one-day discussion on Fire Fighting Foams (attendance approx. 130), and a 2-1/2-day Conference and Workshop on Fireground Command, Control, and Communications (attendance 80) were held. Proceedings of the presentations and discussions are being published.

(4) Surveys of "Advances in the Fire Sciences"

A "Bibliography on Flame Structure", and a manuscript on "Chemistry, Combustion and Flammability Tests" have been prepared. A survey of work in the U.S. and elsewhere on the toxicity of fire gases is being carried out for Committee W14 of the Conseil International du Bâtiment.

(5) Bibliographic Materials

In collaboration with the National Bureau of Standards and the NASA Aerospace Safety Research and Data Institute a "Directory of Workers in the Fire Field" has been published.

A "Fire Sciences Dictionary and Source Book" is in process of being published by John Wiley and Sons, Inc.

(6) Development of a Fire Information System

Although there is general consensus among fire researchers and practitioners that a fire information system would be a valuable asset, no clear statement exists of its mission, its scope of coverage, the public it should serve and what services it would offer.

Following on the summary recommendations at the 1973 Airlie House Conference on "Fire Safety in Buildings" that a Fire Information Clearinghouse be established, the attendees (who represented fire research and building design interests) were requested to comment in greater detail on: extent of fire information areas; awareness and interest in selected published material; the possible functions and scope of a National Clearinghouse (Announcement Services, Information Services, Coverage, Financial Support).

Reports

(1) *"Don't Get Burned"*, a film (23 minutes) produced by the Fire Marshal's Office, Montgomery County, Maryland; the Walter Johnson High School, Bethesda, Maryland; and the Applied Physics Laboratory/The Johns Hopkins University, 1973. Distribution: National Fire Protection Association, Boston, Massachusetts.

(2) *Fire Sciences Dictionary and Source Book*, B. W. Kuvshinoff, R. M. Fristrom, R. L. Tuve (Eds.), to be published by John Wiley and Sons, Inc., New York, 1974.

(3) Proceedings, *The Problems in Teaching the Fire Sciences*, held at the Applied Physics Laboratory/The Johns Hopkins University, March 1-3, 1973, APL/JHU FPP B73-1, November 1973.

(4) Proceedings, *The Teaching of the Fire Sciences*, held at Northern Virginia Community College, April 27-28, 1974 (to be published).

(5) Proceedings, *Fireground Command, Control, and Communications*, held at the Applied Physics Laboratory/The Johns Hopkins University, May 16-18, 1974 (to be published).

FLAME INHIBITION CHEMISTRY

R. M. Fristrom (PI)

C. Grunfelder (Associate Staff)

L. W. Hart (Postdoctoral staff)

N. J. Brown (Postdoctoral staff, presently at University of California, Berkeley)

Cooperating Laboratories:

Institute of Physical Chemistry of the University Göttingen (West Germany) (Dr. K. Hoyermann and Prof. H. Gg. Wagner)

University of California (Berkeley), Departments of Chemistry and Thermal Systems (Dr. N. J. Brown and Prof. R. F. Sawyer)

Laboratory of Physical Chemistry of Combustion at the University of Louvain (Belgium) (Dr. P. Van Tiggelen)

Project Summary

As outlined in the proposal (Ref. 1) this is a continuing project with the objective of understanding the mechanisms involved in flame and fire ignition and extinction.

The goals originally visualized were to develop and test a simplified chemical theory of flame inhibition and prepare a bibliography on flame inhibition and extinction.

During the grant period these goals were modified to place more emphasis on experimental studies and include closer cooperation and exchange of information with laboratories having similar interests. These laboratories with parallel interests include the University of California (Berkeley), the University of Louvain (Belgium), and the University of Göttingen (West Germany). This change was made to accommodate the experimental interests of a new Postdoctoral Research Associate (L. Hart), and the sabbatical of R. Fristrom.

Progress Report and Accomplishments

During the past year (June 1973-June 1974) Flame Inhibition studies have been pursued along several lines. The flame theory work was brought to the level of a routine calculational program and two papers describing the method have been prepared (Refs. 2, 3). Work in this area continues in cooperation with the RANN Fire Program at the University of California, Berkeley (Departments of Chemistry and Thermal Systems).

A new program to study elementary kinetics of inhibitor species under flame conditions was instituted. An apparatus was constructed for the studies and an experimental study of three methyl halides was instituted.

"Abstract*

The "Point Source" technique has been extended to both the direct and relative measurement of first order and pseudo first order reaction rates using flames as high temperature radical baths. Apparatus and technique are described and critically discussed. Measurements of the concentrations of trace gas injected from a point source into a laminar stream were made upstream from the point of injection in order to eliminate the dependence on flow velocity information. The afterburning region of a hydrogen rich hydrogen-oxygen flame provided a laminar stream containing hydrogen atoms. Using a pseudo first-order model, rate constants and rate constant ratios were measured in the temperature range 870-1088K. Two independent methods were used in the data analysis to get measures of absolute rates and rate ratios. Specifically measured were the rate constants $k(H+CH_3Br)$, $k(H+CH_3Cl)$, and $k(H+CH_3F)$ as well as the rate constant ratios $k(H+CH_3Br)/k(H+CH_3F)$, $k(H+CH_3Br)/k(H+CH_3Cl)$, and $k(H+CH_3Cl)/k(H+CH_3F)$. By combining our results with previous work, the constants were evaluated over the temperature range 300-1088K."

The technique and results can be seen in Figs. 2 and 3. The work was reported (Ref. 4) and a manuscript prepared (Ref. 5).

During January-November 1973 R. Fristrom was a guest professor at the Max Planck Institute for Aerodynamics of the University of Göttingen (West Germany), having been awarded a Humboldt Foundation (West Germany) fellowship, given in honor of the 25th Anniversary of

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*Taken from Ref. 5.

the Marshall Plan. Cooperative work on combustion chemistry was undertaken and a joint paper (Ref. 6) on Hydrogen Flame Chemistry was prepared. Related work on NO formation in flames, the point source injection of alkali metal salts in flames and crossed molecular beam studies of elementary reactions were undertaken and are being continued at Göttingen.

Two review papers on Fire Research were prepared and delivered (Refs. 7, 8). Arrangements were made for cooperative programs between APL and the University of Göttingen Institute for Physical Chemistry (Prof. H. Gg. Wagner and Dr. K-H. Hoyermann) in the areas of flame chemistry and flame inhibition. A second agreement to exchange information and if possible people was made with Dr. P. Van Tiggelen, Director of the Physical Chemical Laboratory of Combustion of the University of Louvain (Louvain la Neuve). We believe that cooperation between laboratories which have varying interests, experimental equipment, and talents, but who are all still interested in inhibition of flames,will prove fruitful and should be extended as widely as possible.

Two survey articles on Flame Structure and Flame Sampling were prepared (Refs. 9, 10). Material was collected for a survey on inhibition, but work has not yet begun on the manuscript.

Potential Applications

The information generated by the program appears to have three areas of potential application:

(1) The understanding and modeling of inhibition processes may allow the establishment of a theoretical upper limit for the effectiveness of chemical inhibitors so that we will know whether presently available inhibitors are close to maximum possible effectiveness or whether much remains to be done in the field.

(2) The modeling of inhibition processes could be applied to the design of extinguishment systems.

(3) The chemical kinetic information developed for testing and applying the inhibition models are useful as basic information for chemical rate calculation involving the species studied.

Future Milestones

During the next period (1974-75) the program will be joined by N. deHaas and A. A. Westenberg who will extend the inhibition studies to the kinetics of gaseous inhibitors using ESR techniques (Ref. 11).

Milestones:

July 1974	-	Annual Report
August 1974	-	Apparatus Completion
May 1975	-	Evaluation Report.

Reports 1973-74

(1) FPP Staff - Fire Problems Program Renewal Proposal 1972-74 p.60 ff APL/JHU FPP P2-71 Nov. 1971 Applied Physics Laboratory, Silver Spring, Md.

(2) N. J. Brown, R. M. Fristrom and R. F. Sawyer,"A Simple Premixed Flame Model Including an Application to H_2 + Air Flames" submitted to Combustion and Flame, April 1974.

(3) N. J. Brown, R. M. Fristrom and R. F. Sawyer, "An Elementary Two Zone Flame Model", submitted for Presentation at the 15th International Symposium on Combustion. August 1974.

(4) L. Hart, C. Grunfelder and R. Fristrom, "The Point Source Technique", Fall Meeting of the Eastern States Section of The Combustion Institute, 1973.

(5) L. W. Hart, C. Grunfelder, and R. M. Fristrom, "The 'Point Source' Technique Using Upstream Sampling for Rate Constant Determination in Flame Gases", accepted for publication in Combustion and Flame, May 1974.

(6) N. J. Brown, K. H. Eberius, R. M. Fristrom, K. H. Hoyermann, and H. Gg. Wagner, "Aspects of Chemistry and Mechanisms in some Hydrogen-Oxygen Flames with Added Nitrogen or Hydrocarbon", submitted for presentation at the 15th International Symposium on Combustion, Aug. 1974.

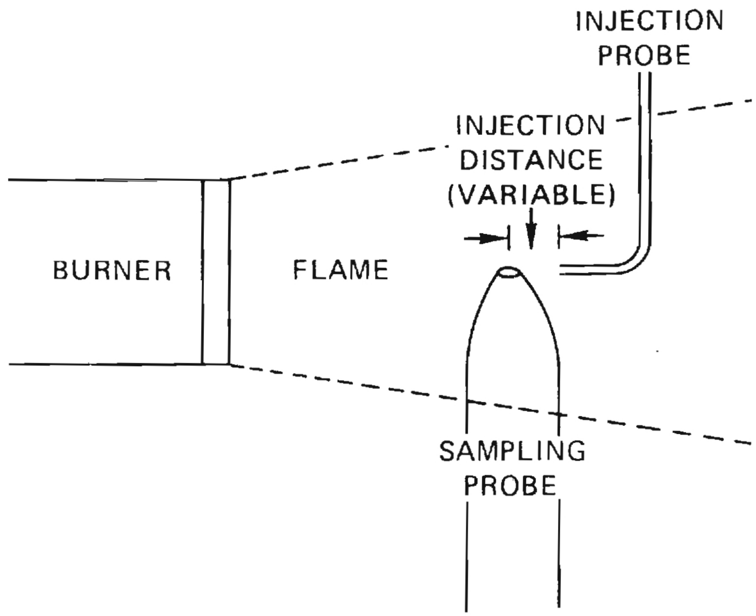
(7) R. M. Fristrom, "Fire Research in the United States", Plenary Lecture at Belgium Section of the Combustion Institute Spring 1973 Meeting to be published in Belgian Annals of Combustion.

(8) R. M. Fristrom, "Some Activities of the Committee on Fire Research of the National Academy of Sciences of the United States", presented at the 3rd. International Conference on Combustion Processes Kassimeriz, Poland, Sept. 1973 (to be published in Polish Archives of Combustion).

(9) R. M. Fristrom, "Flame Structure", APL/JHU FPP S 10, February 1974.

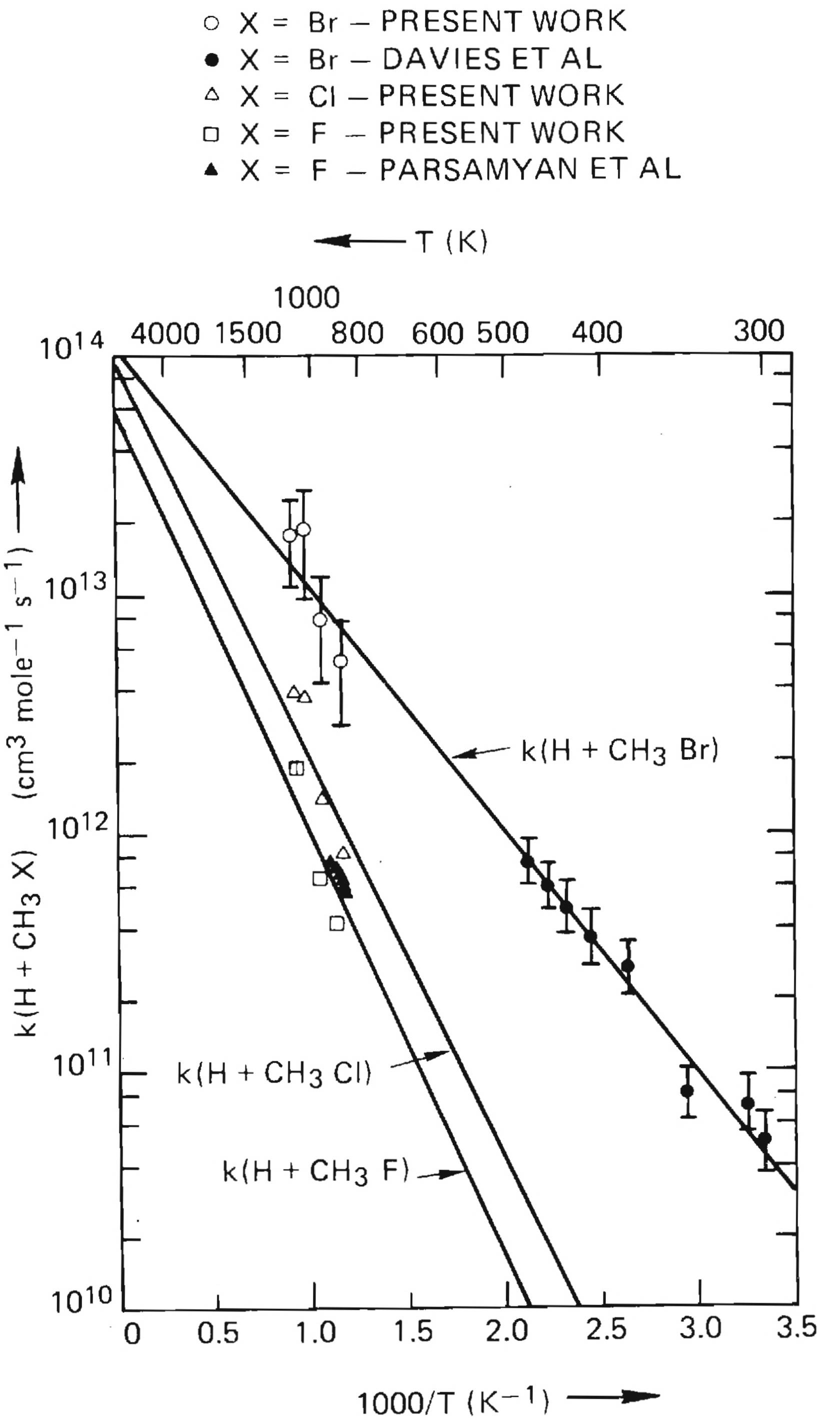
(10) R. M. Fristrom, B. W. Kuvshinoff and M. M. Robison, "Bibliography on Flame Structure 1934-1972", APL/JHU FPP TR 13, January 1974. Accepted for publication Fire Research Abstracts and Reviews, 1974.

(11) A. A. Westenberg, "Use of ESR for the Quantitative Determination of Gas Phase Atom and Radical Concentrations, Progress in Reaction Kinetics, Pergamon Press, Vol. 7, Part 1, p. 23, 1973.



Schematic of Point Source Injection Apparatus for Studying Radical-Molecule Reactions

Fig. 2



An Arrhenius Plot of Overall Rate Constant Ratios of Three Methyl Halides Reacting With Hydrogen Atoms.

Fig. 3

GEORGIA INSTITUTE OF TECHNOLOGY

NSF/RANN CONFERENCE ON FIRE RESEARCH

Georgia Institute of Technology
Atlanta
May 28 and 29, 1974

Institution: Georgia Institute of Technology NSF Grant No. GI-31882

Grant Title: Fabric Ignition

Principal Investigators: W. Wulff School of Mechanical Engineering
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Other Professional Personnel:

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Project Summary:

Rational flammability standards for materials or final products must rationally relate suitable laboratory and field test results to the potential fire loss that could result from the use of such materials or products. The necessary relationships require a quantitative measure of hazard and must accout for, firstly, the stochastic events which lead from product certification to all conceivable hazardous situations and, secondly, the combination of stochastic human behavior in fire with deterministic material response to fire.

Relationships between fire hazard and material properties are being developed in connection with the study of fabric flammability, garment fires and burn injury which apply in principle to the general assessment of fire hazard. The probability with which the use of a garment could lead to a

burn injury is used as the hazard measure. The loss or injury probability is computed from the subsidiary probability of stochastic and deterministic events leading to the fire damage.

Predominantly deterministic events such as ignition, flame propagation, extinguishment, and tissue destruction, are transient, hence the related subsidiary probabilities are functions of characteristic times, specifically of the ratios of the time the process is allowed to proceed over the time the process requires for its completion. Ignition time is the central time characteristic in assessing material or product ignition probabilities.

A modeling analysis is to be developed, using integral techniques, to predict ignition time for pyrolyzing composites undergoing one-dimensional heating. The analysis involves a newly proposed ignition criterion which associates the occurrence of ignition with the attainment of a concentration-dependent temperature in the binary fuel-air mixture near the heated surface.

An experimental program is being performed to measure (1) the lowest ignition temperature of pyrolysate-air mixtures as a function of pyrolysate concentration, (2) the forced convection heat transfer coefficient under simulated pyrolysate evolution, (3) the ignition time of fabrics subject to gas flame heating, (4) the effect of fabric interaction and fabric geometry on fabric ignition time, (5) the probability of fabric ignition under radiative heating, and finally, a program is being carried out to relate laboratory to actual use conditions.

Progress Report

The Third Annual Report, titled "FABRIC IGNITION" and dated March 31, 1974 has been distributed to all NSF/RANN Fire Research Grantees.

Analysis

The ignition modeling analysis has been completed for the prediction of ignition time for single fabrics as shown in Figure 3.2* below. Field equations describing conservation of mixture mass, pyrolysate species, mixture momentum and enthalpy in the binary boundary layer and of energy conservation in the condensed phase are integrated over space and combined with an Arrhenius-type decomposition rate equation to yield five coupled ordinary first-order differential equations. These define the time rates of change of (1) system temperature T, (2) solid decomposition λ, (3) boundary layer thickness H, (4) normalized velocity UH/ν (ν is kinematic viscosity) and surface concentration $w_{f,o}$ of pyrolysate. Results of integrating the five equations are shown in Figures 3.4 and 3.5. Figure 3.6 shows the dependencies of normalized ignition temperature and ignition time on heating intensity.

*Figures are taken from the Third Annual Report.

Experiments

Minimum ignition temperatures have been measured on propane gas in the newly designed and constructed Lowest Ignition Temperature and Concentration Apparatus (LITACA) for test purposes. The gold-plated platinum temperature sensor is currently being replaced by a nickel resistance thermometer because the gold plating, intended to suppress catalytic activity by platinum, did not withstand the ignition temperatures.

Convective heat transfer coefficients are derived from the thermal response of stainless-steel, fine-wire screens. Pyrolysate evolution was simulated through injection of preheated air. Representative relationships between Nusselt number and free-stream Reynolds number, with injection Reynolds number as parameter, are presented in Figure 2.2

Results of fabric ignition time measurements, carried out with gas flame heating, are presented in nondimensional form in Figure 2.6. Shown are the Fourier number, or nondimensional time, of destruction $(N_{Fo})_{i,m} = (k/\delta)/[c(\rho\delta)]\tau_{i,m}$ versus the nondimensional convective heat flux $q_c^* = 2\bar{h}_c(\theta_f - \bar{\theta})/(k/\delta)$ where (k/δ), $(\rho\delta)$ and c represent thermal conductance (W/cm^2C) specific mass (g/cm^2) and specific heat (Ws/gC), respectively $\tau_{i,m}$ is the destruction time (s), $\bar{h}_c$ is the convective film coefficient (W/cm^2C) and $\theta = (T - T_\infty)/(T_{i,m} - T_\infty)$ is the normalized excess temperature above the environmental temperature T_∞, while $T_{i,m}$ is the destruction temperature. The subscript f designates flame property.

The effect of thermal interaction between fabrics, on ignition time, is shown in Figure 2.11 for cotton fabrics subjected to radiative heating.

Ignition probabilities were derived from ignition frequencies, measured under controlled exposure conditions. Typical results are presented in Figure 2.13.

Gas and electric kitchen ranges constitute frequent ignition sources for garment fires. Typical characterizations of such sources in terms of heat flux and temperature distributions are shown in Figures 2.17 and 2.18.

Accomplishments

1. Thermophysical fabric properties were measured on twenty fabrics: (1) heat capacity, (2) thermal conductance, (3) ignition temperature in near-stagnant air, (4) optical properties, (5) reaction calorimetry and kinetics of desorption and pyrolysis.

2. Ignition sources were characterized through measurements of (1) flame temperature, (2) stable species concentration, (3) convective heat transfer coefficients with simulated pyrolysate evolution, and (4) total heat flux distributions.

3. Ignition time measurements were carried out under both convective and radiative heating conditions. Measurements with radiative ignition sources were performed with incident radiant flux levels between 3 and 25 W/cm^2, environmental moisture levels between 10 and 90 percent relative humidity. Gas flame heating experiments were performed with stationary and moving fabric samples.

4. The probability of ignition for given laboratory exposure conditions was determined, through sensitivity analysis, to obey

$$P(I/E) = 1/\sqrt{2\pi} \int_{-\infty}^{X} \exp(-Z^2/2)dZ,$$

where X depends on the ratio of exposure time, τ_e, over the median ignition time $<\tau_i>$

$$X = (\tau_e/<\tau_i> -1)/\sigma$$

The exposure time is here the independent variable, in actual life it characterizes human response to fire. The ignition time is either measured or predicted from modeling analysis. The standard deviation σ was experimentally determined.

5. A new ignition criterion has been developed; an apparatus has been constructed and is being calibrated for the measuring the ignition temperature of pyrolysate-air mixtures, as required for the evaluation of the proposed ignition criterion.

6. An ignition modeling analysis has been developed for predicting ignition time of pyrolyzing composites.

Potential Applications

The conceptual frame work developed is generally applicable to relate fire hazard to laboratory and field tests. The thermophysical fabric properties measured are necessary not only for the study of ignition, but also for the analysis of flame spread and of heat transfer to and from fabrics. The ignition times measured and the modeling analysis developed can serve to assess the relative ease of ignition for the fabrics investigated. Once successfully verified, the proposed ignition criterion would constitute a major advancement in the modeling of ignition processes. The overall program should lead to the rational relation between test methods and burn injury hazard.

Future Milestones

Experimental efforts are directed at relating building fire hazards to laboratory and field test results, specifically at:

(i) Measurement of ignition statistics on thermally thin and thick media.
(ii) Measurement of ignition temperature on pyrolysate-air mixtures as a function of concentration for most frequently employed building materials.
(iii) Modeling experiments on flashover and extinguishment.

Thermally thick media will be analytically modeled.

Reports and Papers

1. Durbetaki, P., Wulff, W., et al., "Fabric Ignition", Third Annual Report, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, NSF (RANN Program) Grant No. GI-31882#1 (1974).

2. Wulff, W., Alkidas, A., Hess, R. W., and Zuber, N., "Fabric Ignition", Textile Research Journal, 43, pp. 577-588 (1973).

3. Wulff, W. and Durbetaki, P., "Fabric Ignition and Burn Injury Hazard", Proceedings, 1973 International Seminar on Heat Transfer from Flames, Trogir, Yugoslavia, to be published by Scripta Publishing Co. (1974).

4. Wulff, W. and Durbetaki, P., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods", Proceedings of the Flammability Characteristics of Materials, Polymer Conference Series, University of Utah, Salt Lake City, Utah, June 11-15 (1973).

5. Wulff, W., Zuber, N., Alkidas, A., and Hess, R. W., "Ignition of Fabrics Under Radiative Heating", Combustion Science and Technology, 6, pp. 321-334 (1973).

6. Durbetaki, P., Wulff, W., et al., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods", Second Final Report, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, NSF (RANN Program) Grant No. GI-31882 (1972), National Technical Information Service Accout Number COM-73-10956.

7. Wulff, W., Zuber, N., et al., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods", Final Report, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, NSF Grant No. GK-27189 (1971), National Technical Information Service Account Number COM-73-10954.

Theses

completed:

1) Kirkpatrick, Carrol Stone, "A Study of the Preignition Behavior of Selected Garment Fabrics and Consequent Burn Injury Probability", June 1972. (M.S. Thesis)

2) Giddens, William Edgar, "Reaction Kinetics of Fabrics", March 1973. (M.S. Thesis)

3) Champion, Edward Ray, "Determination of Fabric Ignition Times Through Use of a Convective Heat Source Apparatus", June 1973. (M.S. Thesis)

4) Naveda, Oscar A., "Study of Actual Ignition Sources of Clothing", May 1974. (M.S. Thesis)

in progress:

1) Acree, Robert Leighton, "Fabric Ignition Time Under Various Geometrical Configurations". (M.S. Thesis)

2) Wedel, Gregory L., "Determination of Film Coefficients with Simulated Pyrolysate Injection". (M.S. Thesis)

3) Williams, Paul Thomas, "Ignition Temperatures of Pyrolysate-Air Mixtures". (M.S. Thesis)

Invited Lectures

1. W. Wulff, "Fabric Ignition", 164th National American Chemical Society Meeting, New York, August 27-September 1, 1972.

2. W. Wulff & P. Durbetaki, "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods", University of Utah, Salt Lake City, 1973.

3. W. Wulff & P. Durbetaki, "Fabric Ignition and Burn Injury Hazard", International Seminar on Heat Transfer from Flames, Trogir, Yugoslavia, 1973.

4. W. Wulff & P. Durbetaki, "Ignition Probability and Fire Hazard", Engineering Science and Mechanics Seminar, Georgia Institute of Technology, Atlanta, Georgia, September 27, 1973.

5. P. Durbetaki & W. Wulff, "The Georgia Tech Fabric Flammability Research", Third Flame-Free Design Conference, The Marriott Hotel, Atlanta, Georgia, March 13 through 15, 1974.

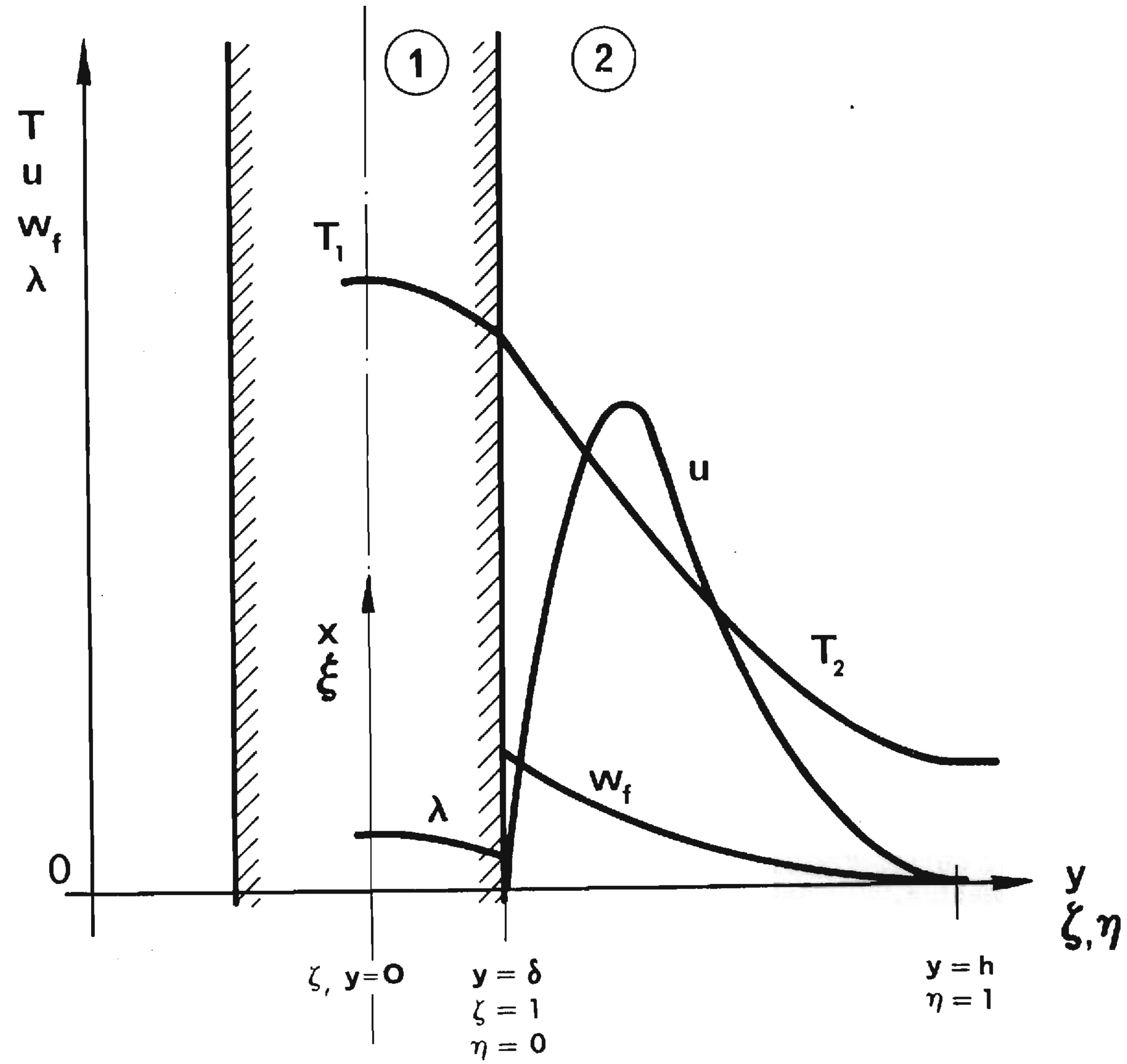

Figure 3.2 Two-Region System and Nomenclature

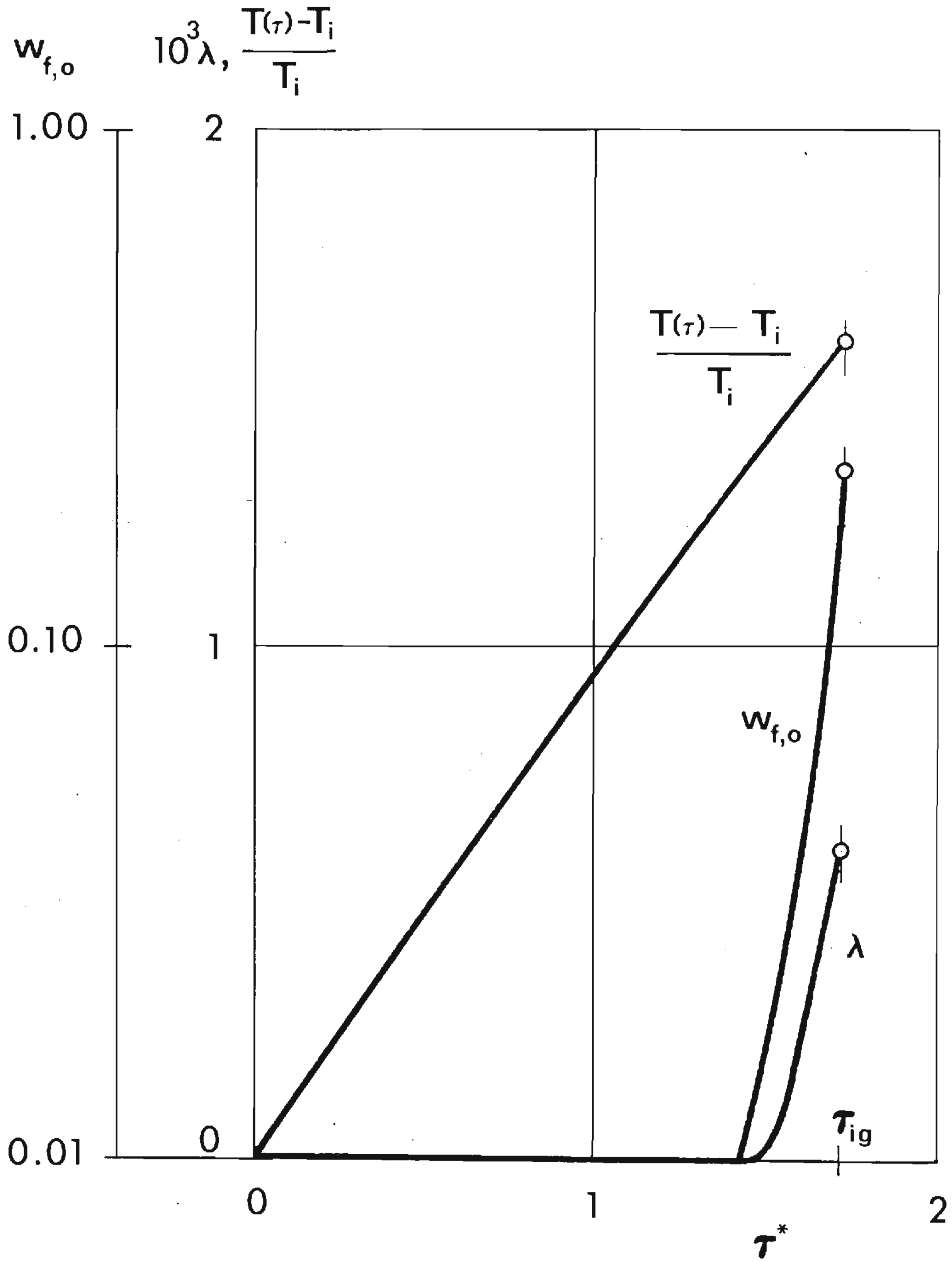

Figure 3.4 Temperature Rise $T/T_i - 1$, Decomposition λ and Surface Pyrolysate Concentration Histories During Preignition Process

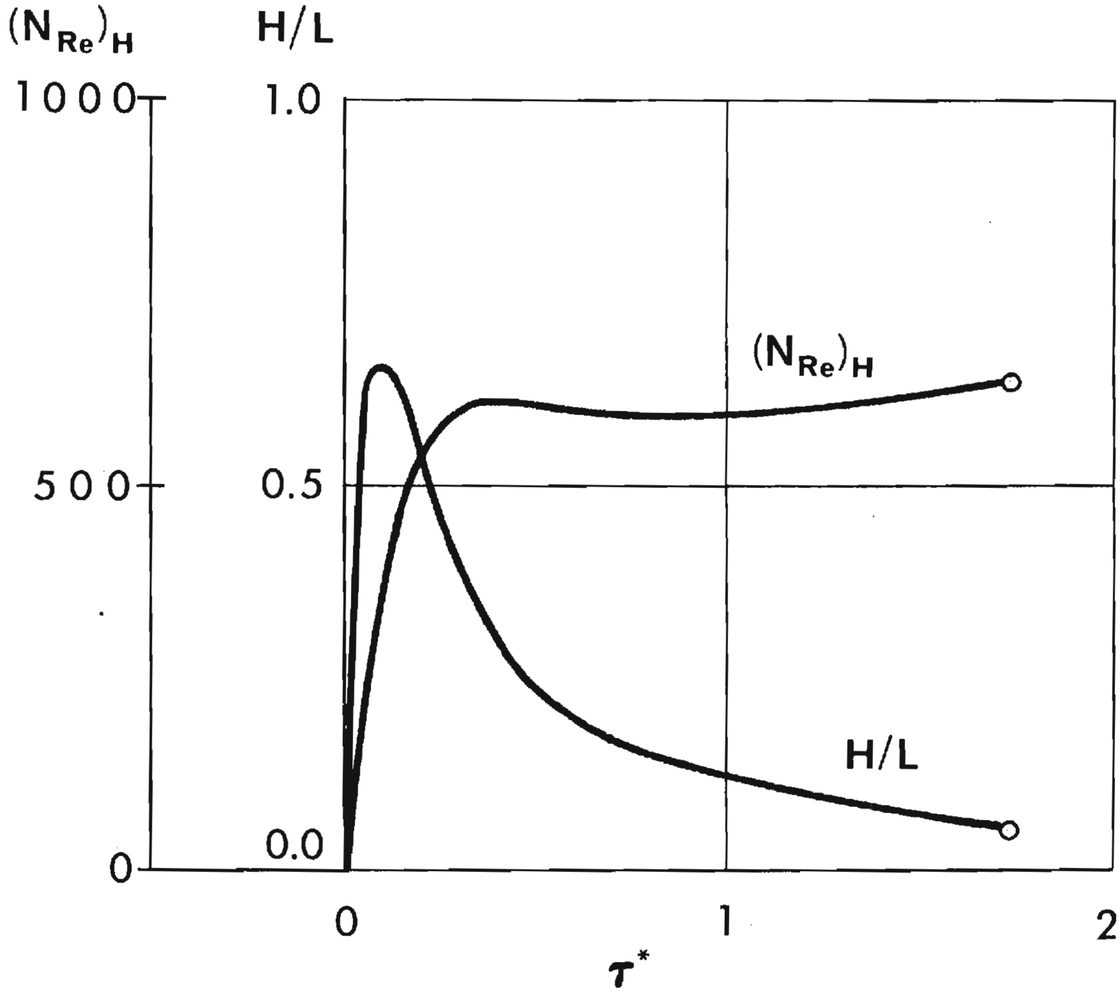

Figure 3.5 Fluid Dynamics During Preignition Process. Reynolds Number and Normalized Boundary Layer Thickness versus Normalized Time

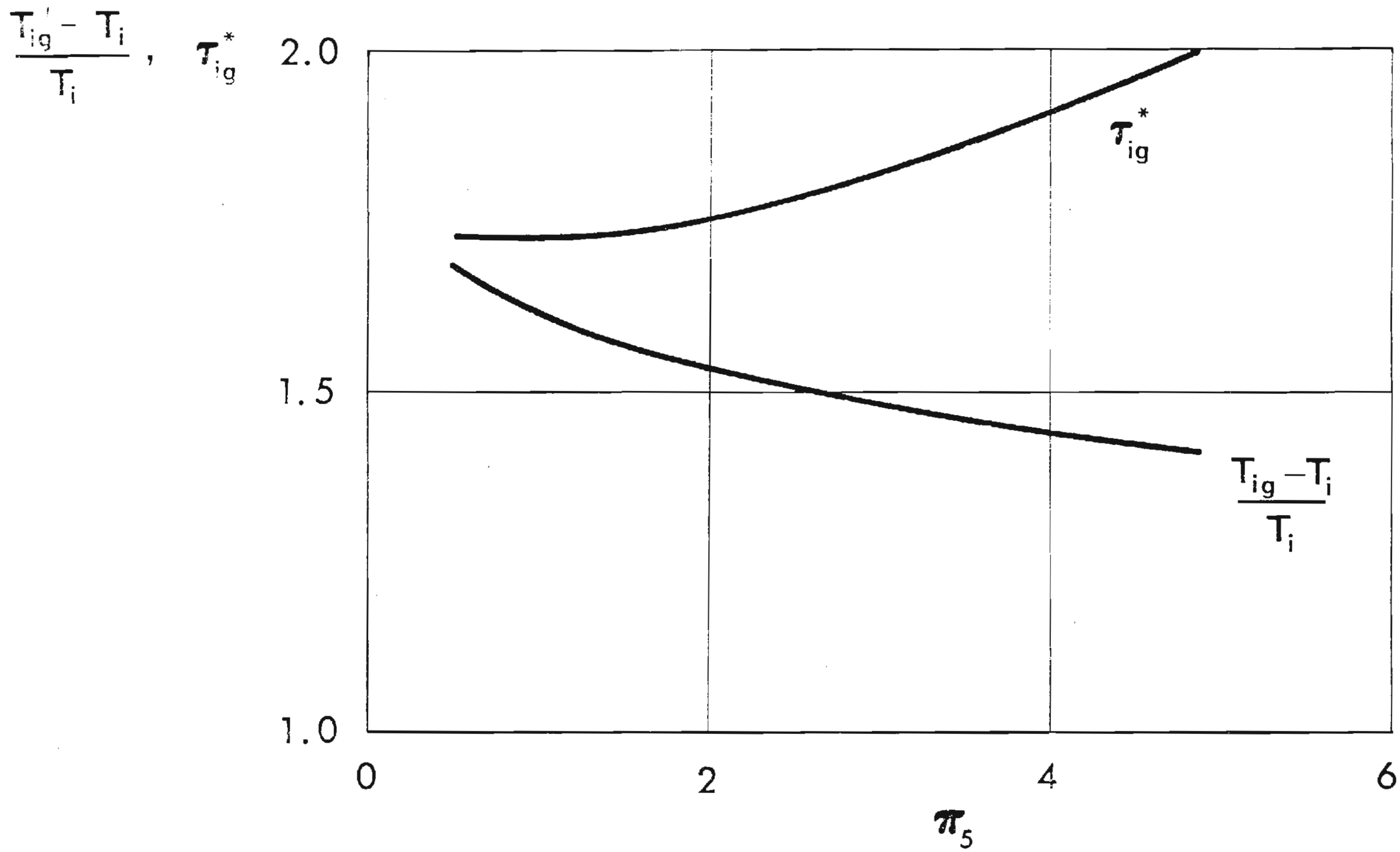

Figure 3.6 Ignition Time and Ignition Temperature Dependences on Heating Intensity. Heating Intensity Decreases from Left to Right.

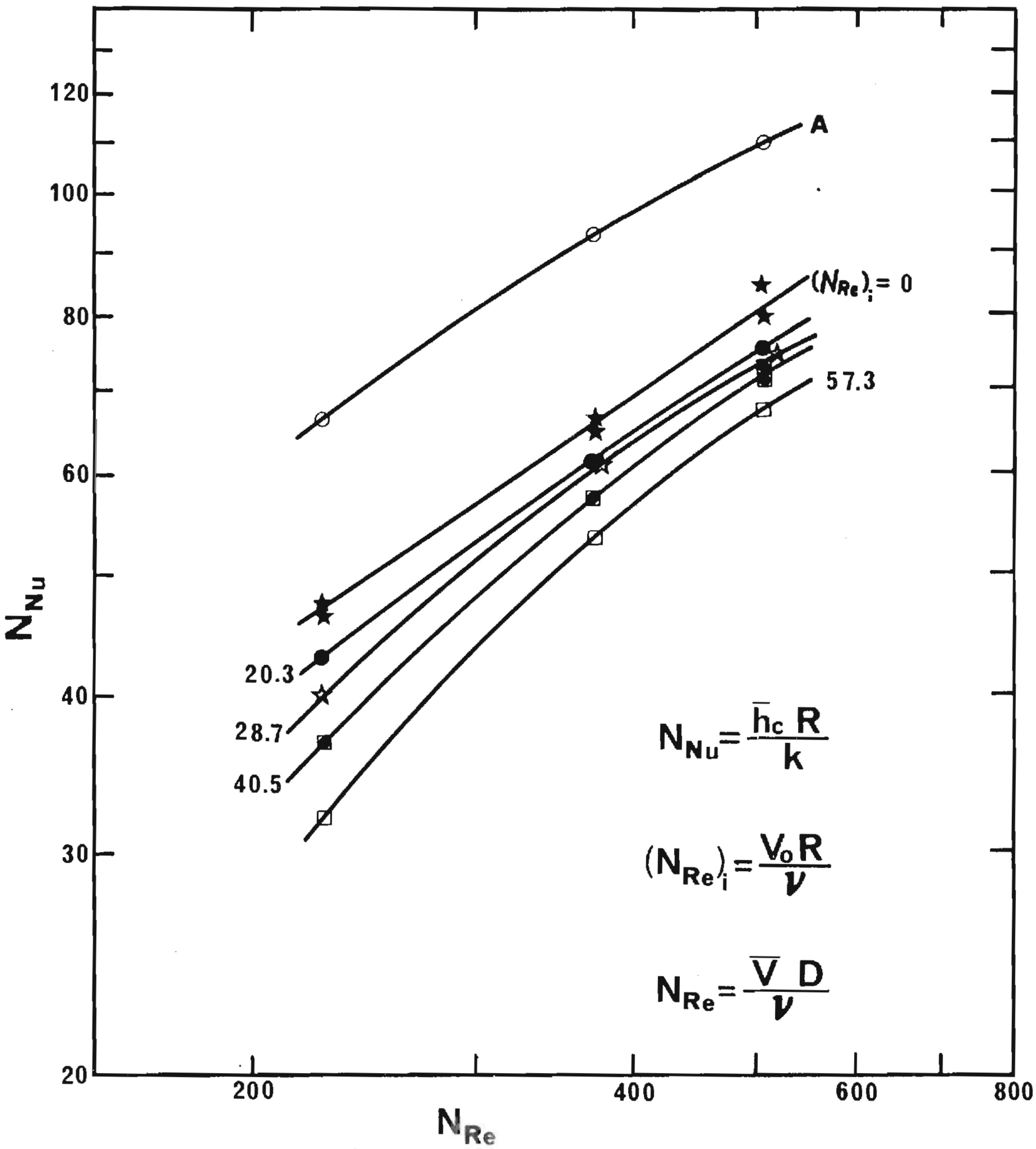

Figure 2.2 Nusselt Number vs. Free-Stream Reynolds Number with Injection Reynolds Number as Parameter, for Low Injection Gas Temperature

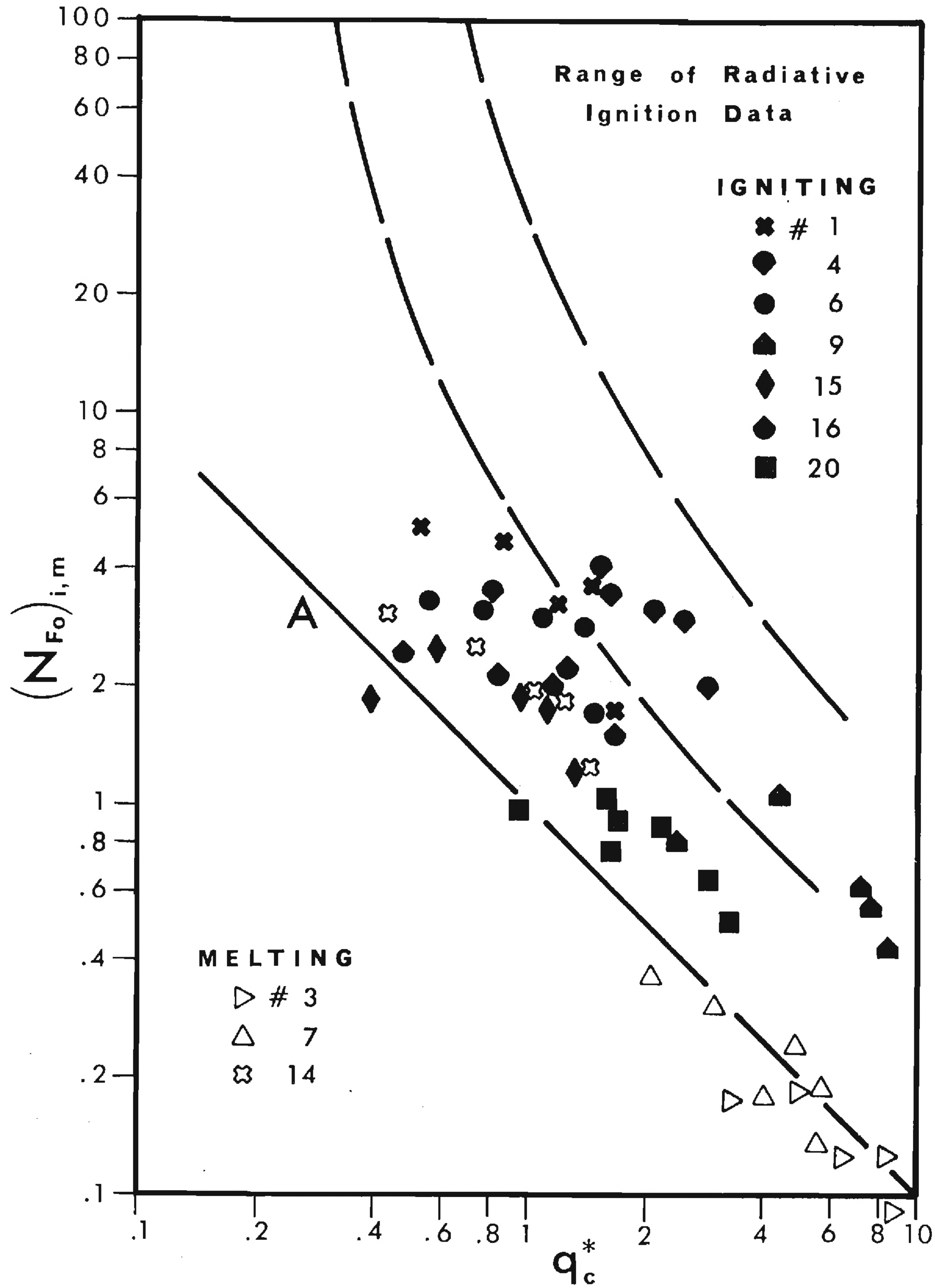

Figure 2.6 Normalized Destruction Time vs Normalized Convective Heat Flux for the Secondary GIRCFF Fabrics

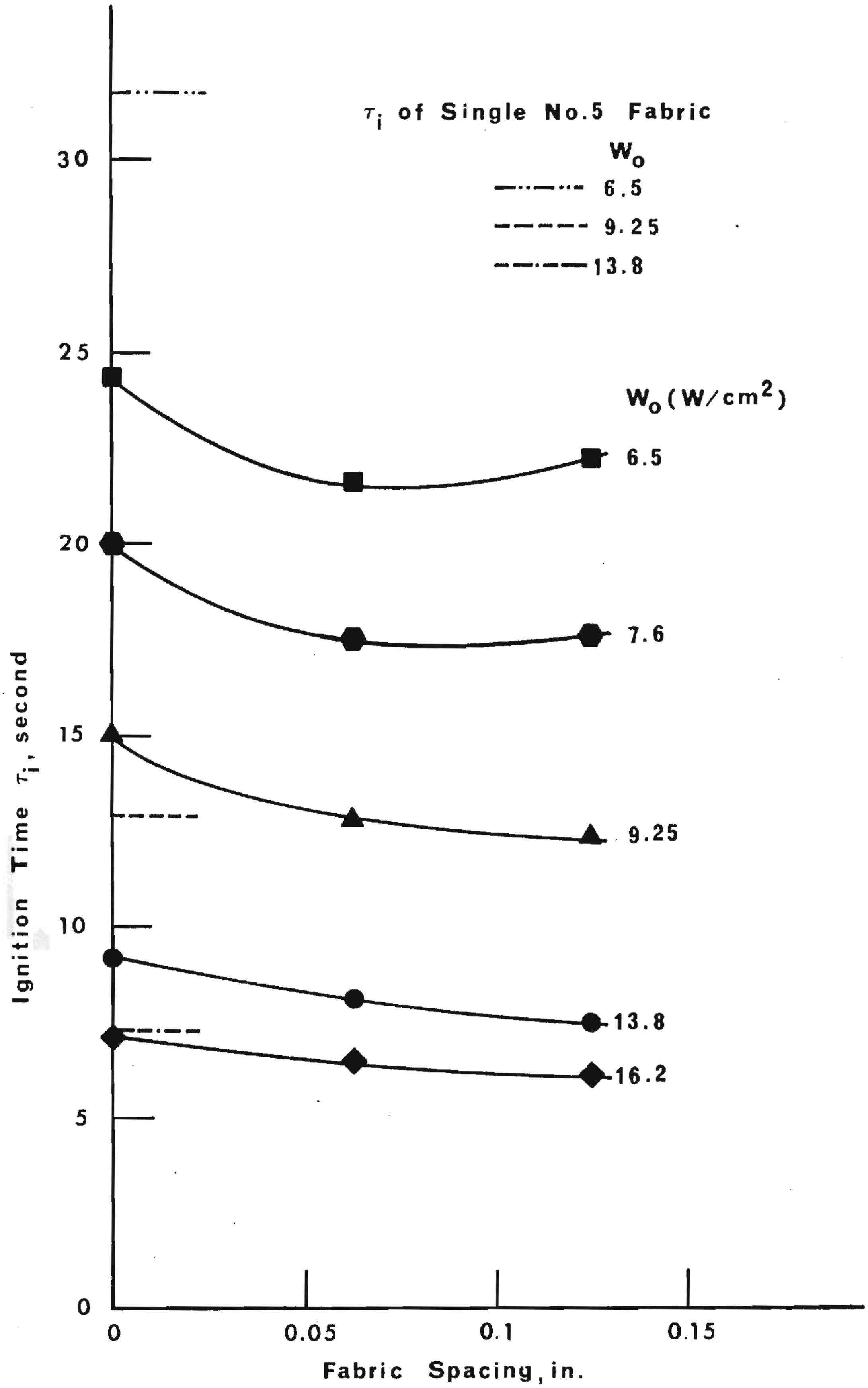

Figure 2.11 Ignition Time of Two-Fabric Composites as Function of Spacing GIRCFF Fabric No. 5, Cotton

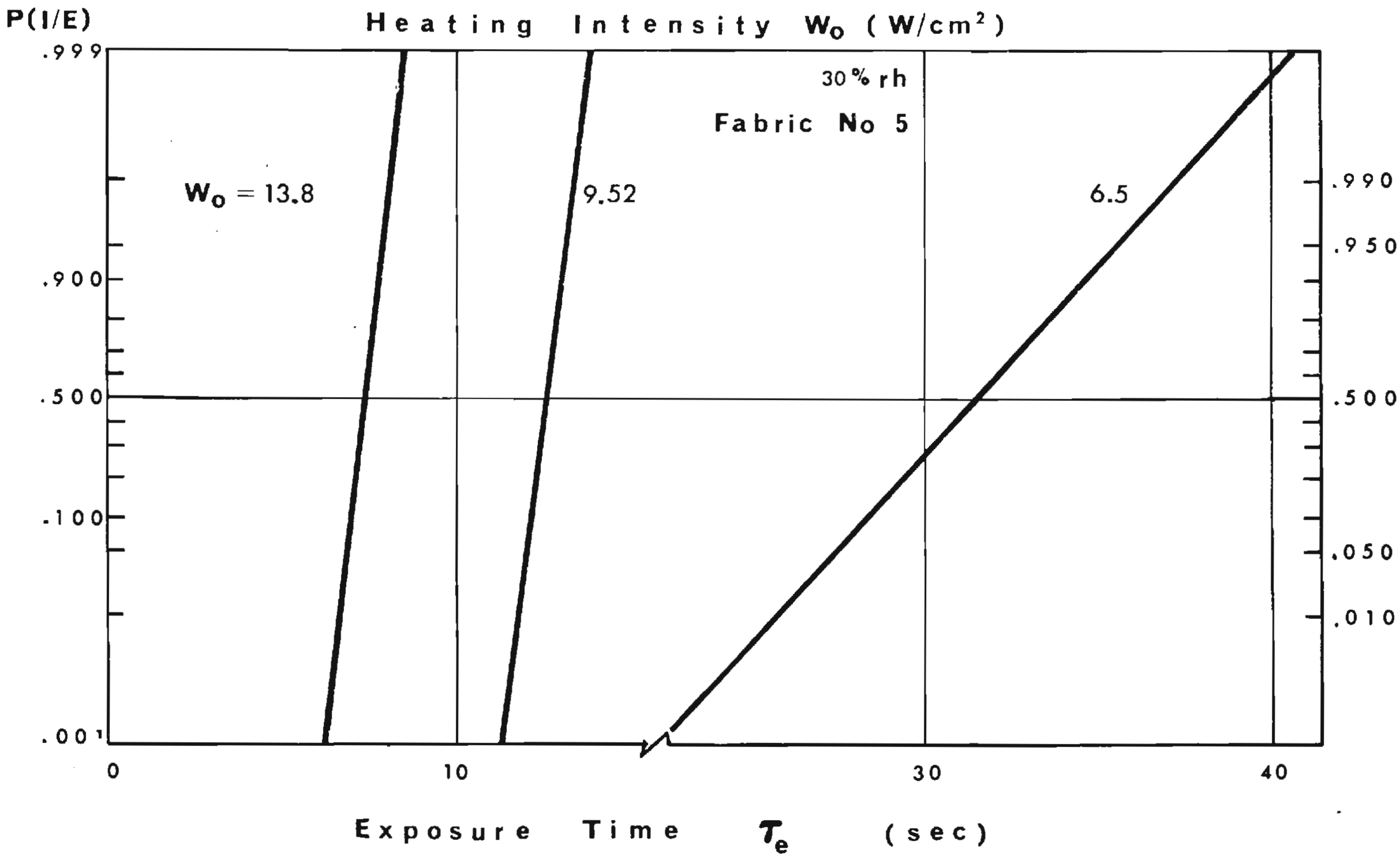

Figure 2.13 Ignition Probability as Function of Exposure Time and Heating Intensity, at 30% r.h. Cotton, GIRCFF Fabric No. 5

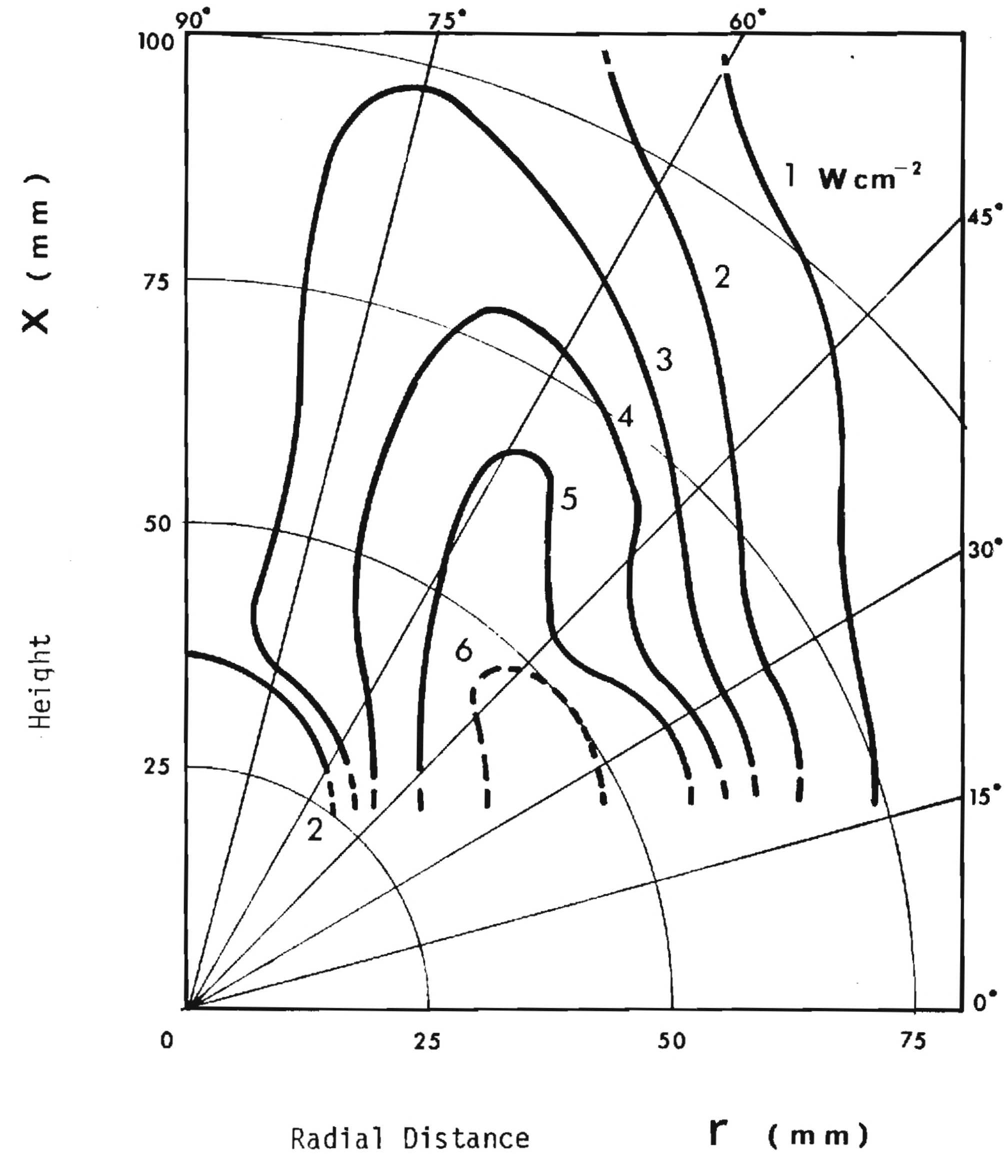

Figure 2.17 Total Heat Flux Distribution, Kenmore Kitchen Gas Range Model 119.15031, Full Open Burner

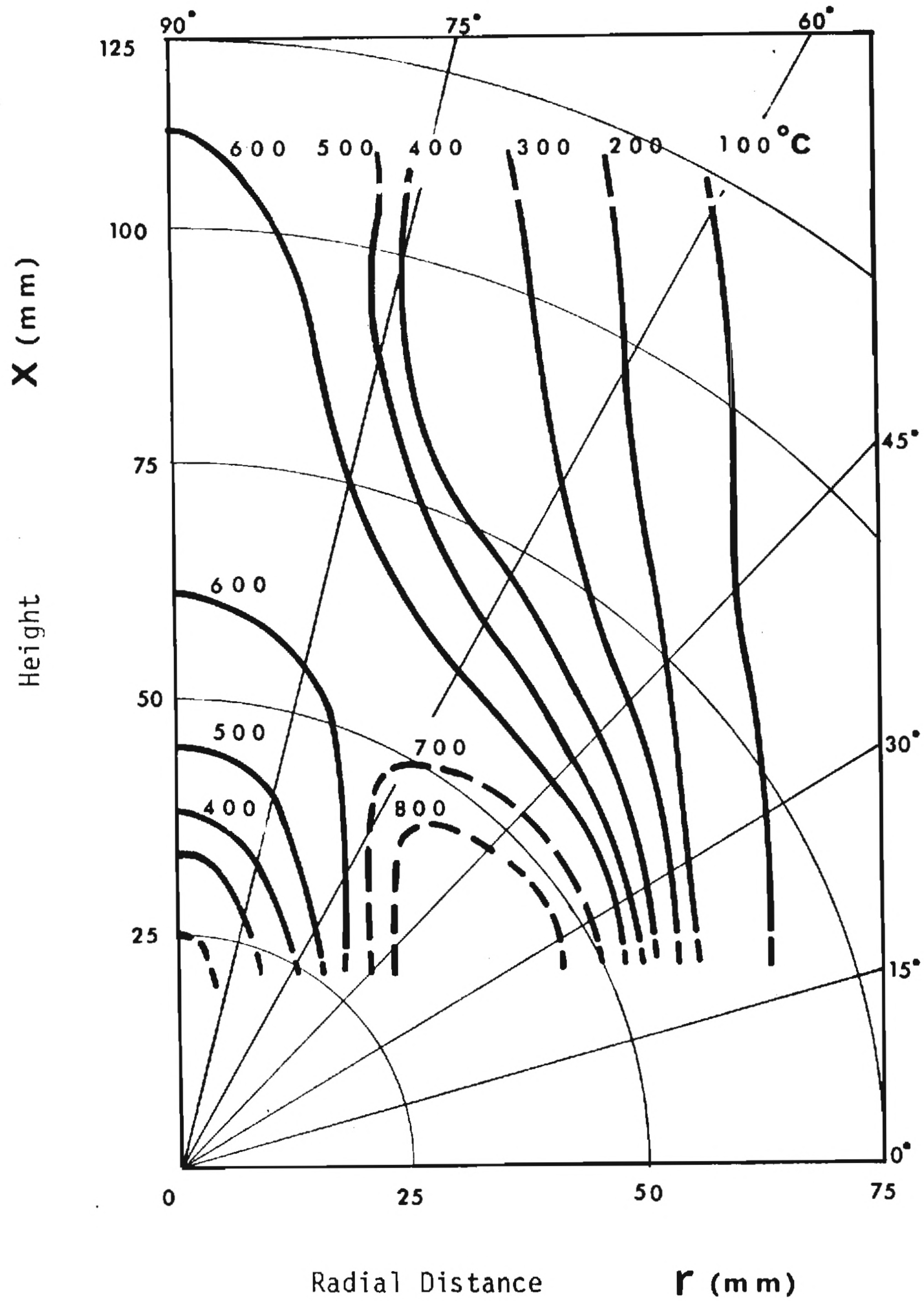

Figure 2.18 Temperature Distribution, Kenmore
Kitchen Gas Range Model 119,15031, Full Open Burner

TEXTILE RESEARCH INSTITUTE

Institution

Textile Research Institute

NSF Grant No.

GI-37805

Grant Title

The Thermal and Flammability Behavior of Multicomponent Fibrous Polymer Systems

Principal Investigator

Dr. Bernard Miller, Textile Research Institute, P. O. Box 625, Princeton, N.J. 08540 - (609)-924-3150

Other Professional Personnel

Dr. J. R. Martin, Staff Scientist, TRI
Mr. C. H. Meiser, Jr., Staff Scientist, TRI

Project Summary

The basic purpose of this research program is the establishment, in rigorous quantitative terms, of the thermal and flammability characteristics of multicomponent fibrous polymer systems. The initial phase of this program is concerned with experimental studies on various polymer combinations to establish what would be normal (i.e., noninteractive) behavior for mixed systems, and to identify those mixtures that give indications of interaction during thermal decomposition and/or burning.

Progress Report

An analytical evaluation of flammability behavior can only be carried out in terms that describe the sequence of events and consequences that make up the overall burning process. These steps can be divided conveniently into pre-ignition and post-ignition categories. Based on this rationale, quantitative studies on multicomponent polymer systems are being performed to determine the following:

Pre-ignition events

Thermal decomposition temperatures
Enthalpy changes before and during thermal decomposition
Products of thermal decomposition
Kinetics of the ignition process

Post-ignition events and consequences

Products of combustion
Flame temperatures
Heat emission during burning
Flame propagation rates
Mass burning rates
Acceleration of burning
Extinguishability

Data for some of the above parameters can be obtained using conventional equipment and techniques (e.g., thermal analysis, gas chromatography, etc.). For other cases (ignition kinetics, acceleration of burning, extinguishability, etc.) new experimental techniques have been developed and utilized.

Results obtained up to this time are sufficient to allow the presentation of a set of definitions and descriptions, covering most of these parameters, of what should be normal or noninteractive behavior for a mixed system. These criteria are listed in Table I.

Based on the above guidelines for noninteractive behavior, a variety of combinations are being studied to identify those that show unexpected (interactive) behavior. The results obtained so far are summarized in Table II, showing which systems exhibit interactive behavior and which do not. In some cases, a combination will show symptomatic interactive behavior for all aspects of its flammability behavior; in other cases interaction has been observed for some properties but not with others.

In addition, the combination of nylon and cellulose, which appears to be the most obvious case where interactions are likely to be occurring, has been investigated in somewhat more depth. The object of this study is the elucidation of the chemical mechanism of interaction through use of the more classical analytical techniques. The results obtained at this time indicate quite definitely that an early decomposition product of the polyamide effects a chemical modification of the cellulose, producing a material with somewhat different flammability properties.

REPORTS AND PUBLICATIONS

Completed:

"Progress Report No. 1" to the National Science Foundation, November 30, 1973.

"The Autoignition of Multicomponent Fiber Systems", B. Miller, J. R. Martin and C. H. Meiser, Jr., in "Polymers and Ecological Problems", J. Guillett, Editor, Plenum Press, 1973.

In preparation:

"Progress Report No. 2", to the National Science Foundation.

"The Measurement of Burning Accelerations of Unrestrained Fabrics".

"The Flammability Behavior of Multicomponent Polymer Systems".

"Chemical Interactions During Heating of Polyamide-Cellulose Mixtures".

TABLE I

CRITERIA FOR NONINTERACTIVE BEHAVIOR OF MULTICOMPONENT SYSTEMS

THERMAL DECOMPOSITION TEMPERATURES	Unchanged
ENTHALPY CHANGES	Unchanged
PRODUCTS OF THERMAL DECOMPOSITION	Equal to the sum of the contributions from the individual species
KINETICS OF IGNITION PROCESS	Identical to that of the faster igniting component
FLAME TEMPERATURE	Equal to that of the hotter burning component
HEAT EVOLUTION DURING BURNING	Equal to the weighted average amount of heat produced by the components of the mixture
FLAME PROPAGATION RATE	Equal to that of the faster burning component
ACCELERATION OF MASS BURNING RATE	Equal to that of the faster accelerating component

TABLE II

THERMAL AND FLAMMABILITY RESPONSES OF MIXED FABRIC SYSTEMS
(I=Interaction detected; N=Noninteractive or normal behavior)

	THERMAL DECOMPOSITION	IGNITION KINETICS	FLAME TEMPERATURE	HEAT EMISSION	FLAME PROPAGATION	ACCELERATION OF UPWARD BURNING
Nylon-Cellulose	I	I	I	I	I	I
Polyester-Cellulose	I	I	N	N	I	N
Acrylic-Cellulose	-	N	N	I	N	N
Polyester-Wool	-	-	I	I	I	I
Polyester-Nylon	I	I	I	-	I	I
Polyester-Acrylic	-	-	N	-	N	I
Nylon-Acrylic	-	-	I	-	N	N
Wool-Nylon	-	-	I	-	I	I
Wool-Acrylic	-	-	I	-	I	I
FR Cotton*-Polyester	-	-	N	-	I	I
FR Polyester**-Cotton	-	-	I	-	I	N
FR Cotton*-Acrylic	-	-	N	-	I	I
Cellulose-Nomex®	-	N	I	-	I	I
Cellulose-Glass	-	N	I	-	N	I
Nomex®-Glass	-	N	-	-	-	-

*Cotton plus 1.2% Diammonium Phosphate (DAP)

**PET plus 7.4% Tris-2,3-Dibromopropyl Phosphate (T23P)

UNIVERSITY OF MONTANA

NSF Grant No.: GI-33645x1

Institution: Wood Chemistry Laboratory
University of Montana
Missoula, Montana 59801

Grant Title: Chemistry of Cellulosic Fires

Principal Investigator: Fred Shafizadeh
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Research Associates: Yuan-Zong Lai, Ronald A. Susott, Hans Lundstrom, Susumu Ishiguro, and Ping-sen Chin

Research Assistant: William DeGroot

Project Summary:

The principal objectives of this program are to unravel the complex chemical reactions which lead to the combustion of cellulosic materials and to determine various mechanisms for controlling them.

Progress Report:

The breakdown of cellulosic macromolecules to combustible tar and volatile products were investigated by pyrolysis of a variety of model compounds containing the same monomeric units such as glycosides, levoglucosan, disaccharides, and finally, cellulose. These stuides showed that the free hydroxyl group present on different positions of the sugar unit substitutes the glycosic bonds. The substitution or transglycosylation results in the breakdown of the macromolecule to a heterogeneous mixture of anhydrosugars and oligosaccharides. These compounds are the main component of tar and progenitor of the combustible gases, char, and water which are formed on further heating.

Fission of the sugar units provides the combustible gases (mainly small carbonyl molecules) which feed the flames. Dehydration of the sugar units provides mainly water, carbon dioxide, and char which extinguish or retard the combustion process. The dehydration pathway has been defined by analysis of the intermediate products and investigation of their thermal properties.

Recognition of the competing pathways for combustion of cellulosic materials has significant implications in determining the effective heat content of natural fuels and in determining the mechanism and significant factors involved in flameproofing. Extensive investigation of the phosphate and halide flame retardants has shown that these materials promote the dehydration and charring reactions (see the attached table). In the early stages of pyrolysis, more than 10% levoglucosenone (one of the initial dehydration products) was formed on adding small quantities of the flame retardant or partial substitution of the hydroxyl groups with phosphate or chlorine groups.

The above data show that flameproofing may be achieved by promoting dehydration and charring in the solid phase in addition to preventing the combustion of the fission products in the gas phase. Under the pyrolytic conditions, the substituents are eliminated as the corresponding acids to exert a catalytic effect. In each case 80-90% of the phosphate additive or substituent is found in the char. The apparent reason for high efficiency of the phosphate retardants is availability of the reactive species during decomposition of the substrate. These results and other information obtained with nitrogen compounds indicate that the efficiency and synergistic effect of the flame retardants are related to the coordination of the pyrolytic properties of the substrate and the retardants and the coordinated effect of the reactive species generated by the flame retardant.

Accomplishments:

1. The mechanism for the breakdown of cellulosic materials to flammable tars and volatile products and the composition of these materials has been determined.

2. Essential features of the suppression mechanism has been established.

3. Investigation of several flame retardants have shown the mechanism of the chemical interactions involved.

Potential Applications:

1. The effective heat content of different natural fuels is determined as a function of their chemical composition and the possibility of charring and dehydration which reduces the combustion heat available for propagation of fire. The results will be incorporated in a mathematical model which is being developed at the Northern Forest Fire Laboratory of the U. S. Forest Service to predict the behavior of forest fires.

2. The resulting information on flame retardants provides a chemical knowledge of the significant factors such as the reactive species, catalytic effects, efficiency, synergistic interactions, and intermediate products which must be considered in the formulation, application, and testing of the flame retardants.

Future Milesones:

1. Completing the studies on mechanism of suppression reactions involving dehydration, carbonization, and decarboxylation.

2. Completing the studies on mechanism of flame retardants including halogens, Lewis acids, water, boron and complex compounds.

Reports:

F. Shafizadeh, M. H. Meshreki, and R. A. Susott, "Thermolysis of Phenyl Glycosides," *J. Org. Chem.*, 38, 1190 (1973).

F. Shafizadeh and Y. L. Fu, "Pyrolysis of Cellulose," *Carbohyd. Res.*, 29, 113 (1973).

F. Shafizadeh, "Cellulose Chemistry: Perspective and Retrospect," *Pure and Appl. Chem.*, 35, 195 (1973).

F. Shafizadeh and R. A. Susott, "Crystalline Transitions of Carbohydrates," *J. Org. Chem.*, 38, 3710 (1973).

F. Shafizadeh and Y. Z. Lai, "Thermal Rearrangements of Cellobiose and Trehalose," *Carbohyd. Res.*, 31, 57 (1973).

F. Shafizadeh and Y. Z. Lai, "Thermal Degradation of 2-Deoxy-D-*arabino*-hexonic Acid and the 1,4-Lactone," (manuscript being revised).

F. Shafizadeh and Y. Z. Lai, "Thermal Degradation of 3-Deoxy-D-*erythro*-hexosulose," (manuscript being revised).

F. Shafizadeh, G. D. McGinnis, R. A. Susott, and M. H. Meshreki, "Thermolysis of Aminosugar Derivatives," *Carbohyd. Res.*, (in press).

Pyrolysis Products of Cellulose and Cellulose Diphenyl Phosphate
at 600° under nitrogen

Product	Cellulose treated with Diphenyl Phosphate (% amount of sample)							Cellulose Diphenyl Phosphate (% amount of sample)				
	Diphenyl Phosphate Content(%):							Degree of Substitution:				
	0	5	7.5	10	20	30	60(EM)	0.02	0.09	0.13	0.49	0.91
	Phosphorus Content(%):							Phosphorus Content(%):				
	0	0.62	0.93	1.24	2.48	3.72	7.44	0.4	1.47	2.07	5.51	7.56
Acetaldehyde	2.9	0.7	0.6	0.5	0.3	0.2	T	1.9	0.6	0.4	0.1	T
Furan	1.7	0.9	0.9	0.8	0.7	0.8	0.4	1.4	0.7	0.6	0.2	T
Propenal	1.2	0.4	0.4	0.4	0.2	0.2	T	0.8	0.4	0.4	T	T
Methanol	1.8	1.4	1.4	1.2	0.8	1.0	1.2	2.0	1.2	1.2	1.8	2.8
2-Methylfuran	0.4	0.8	0.8	1.1	1.0	1.1	1.9	0.8	1.0	1.5	1.5	2.0
2,3-Butanedione Benzene	1.8	2.4	2.2	2.4	2.4	2.8	9.6	1.8	2.2	2.4	3.0	6.8
2-Butenal	0.5	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.1	T
1-Hydroxy-2-propanone Glyoxal	1.2	T	T	T	T	T	T	T	T	T	T	T
Acetic Acid	1.8	1.5	1.7	1.5	1.4	1.2	2.0	1.6	1.3	1.5	2.2	3.8
2-Furaldehyde	1.6	1.5	1.6	1.5	2.0	2.4	4.2	1.5	1.4	1.5	1.6	1.2
Benzofuran	--	T	T	0.2	0.4	0.6	1.5	T	T	T	0.1	0.4
5-Methyl-2-Furaldehyde	0.4	0.4	0.5	0.4	0.5	0.6	1.1	0.5	0.7	0.8	2.1	2.5
Char	7.0	26.3	28.2	32.5	35.8	32.5	32.8	18.7	31.1	36.0	36.1	41.5
Water	9.7	18.3	22.7	17.0	18.8	15.0	12.7	13.3	18.5	15.8	14.2	12.6
Balance(tar, CO_2, Phenol)	68.0	45.1	38.8	40.3	35.5	41.4	32.3	55.4	40.7	39.7	37.0	26.4

SUNY AT BINGHAMTON

Institution: State University of New York at Binghamton

NSF Grant No.: I035338

Grant Title: Extinction of Flames by Powders of Metallic Salts

Principal Investigator: Walter E. Kaskan
Department of Chemistry
State University of New York at Binghamton
Binghamton, New York 13901
(607) 798-2298

Other Professional Personnel: Dr. Sridhar Iya - Post Doc
Susan Wollowitz - Undergraduate Student
Kim Hayes - Undergraduate Student

Project Summary:

Objective: To try to determine whether inhibition by metallic salts is heterogeneous or homogeneous, and to determine the chemical mechanism.

Research Plan: Determine whether or not there is a correlation between degree of inhibition and the concentration of evaporated species, independent of other factors such as particle size.

Progress Report:

Observations are being made on premixed methane-air flames burning at one atmosphere on a flat flame burner. The uninhibited flame is partially quenched, i.e., burning so close to the burner surface that it transfers an appreciable amount of heat to it. As it is inhibited it transfers less heat and the flame temperature rises. Thus a measure of the degree of inhibition is the amount of temperature rise in the flame. Physically it is measured by Li 6708 Å line reversal.

The measure of the vaporized species from the sodium salts studied is the Na atom concentration at the end of the reaction zone. These are determined by optical absorption.

Two salts have been employed, the bicarbonate $NaHCO_3$, and the tartrate $Na_2C_2H_4O_6 \cdot 2H_2O$. Samples of each were "siliconized" to improve dispersability and classified into a number of particle size fractions.

The data obtained for a $\phi = 1.2$ CH_4/air flame are shown in Fig. 1. Here ΔT is the temperature rise on salt addition, plotted against the Na atom concentration. ΔT is measured from the clean quenched flame temperature of 1800°K, which may be compared with the adiabatic flame temperature of 2100°K for this mixture. The points for all particle sizes of both salts are seen to lie on the same line within experimental error. Similar results were obtained for a stoichiometric flame. Thus a good correlation is obtained.

Before this can be interpreted as evidence for the homogeneous mechanism, some idea of the fate of the particles in the flame had to be obtained. Figure 2 shows Na atom concentrations as a function of distance from the flame zone for several particle fractions. The flame zone proper is between 0 and 2 mm. It is seen that the four smaller particle sizes are completely evaporated by the end of the flame zone. Amongst the tartrate fractions there is a five fold variation in the specific area presented to the flame, but the inhibition is more nearly related to the total, evaporated salt. We take this as almost conclusive evidence that the inhibition is homogeneous.

We are currently making measurements of the OH concentration in inhibited flames in an attempt to shed light on the chemistry of inhibition. So for it has been determined that the presence of Na atoms causes a catalysis of the recombination of OH, and that the effect is surprisingly efficient. Work is still in progress in this area.

Accomplishments:

1) Have developed an almost conclusive case that inhibition by sodium salts, and by implication the salts of the other alkalies, is homogeneous.

2) Have provided data, for the first time as far as we know, on actual evaporation rates of particles in flames.

Potential Applications:

The work implies that the most effective salt inhibitors are those that vaporize most easily, and provides a method for measuring evaporation.

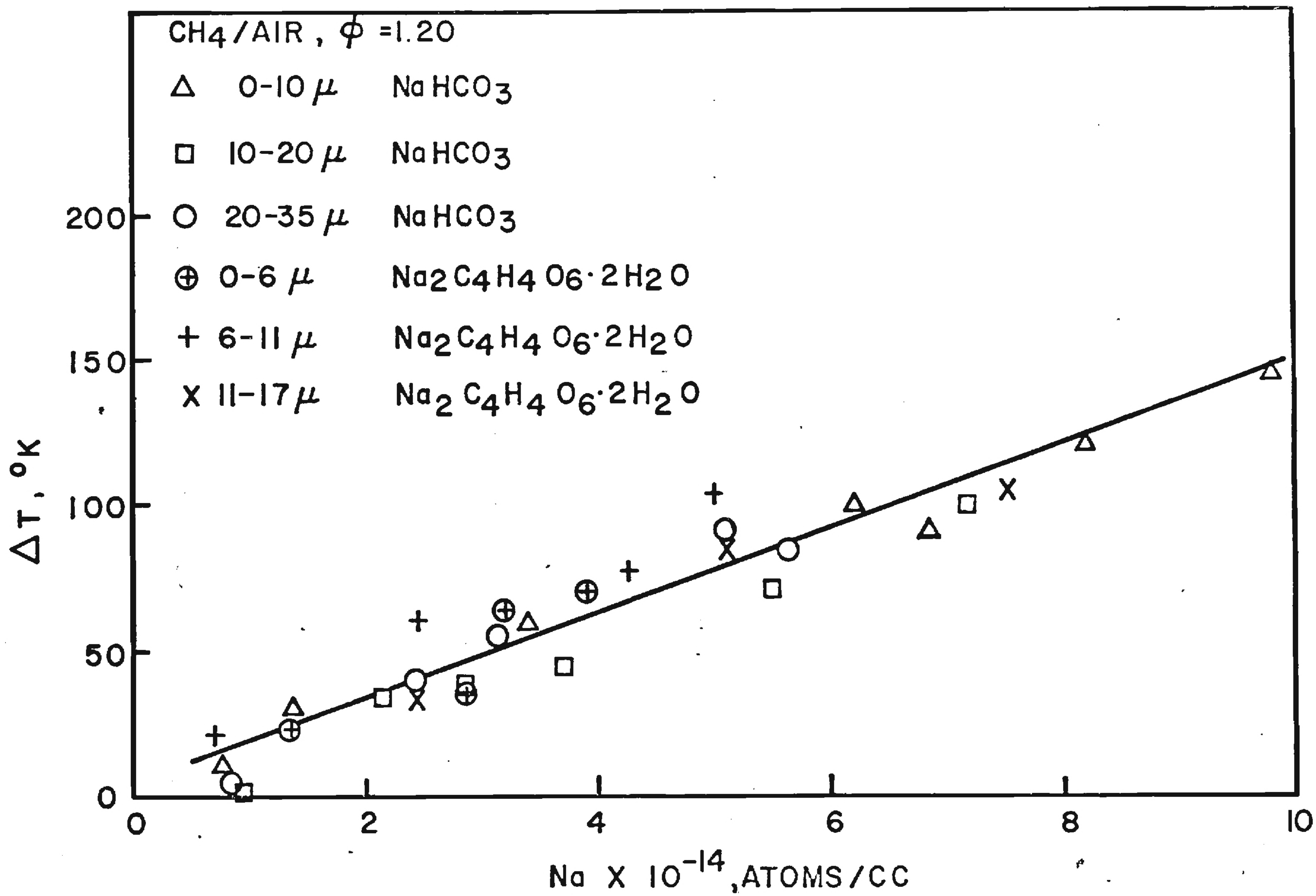
Future Milestones:

The principal thing we hope to yet accomplish is to develop a mechanism for the catalysis by Na atoms of the free radical recombination, and to determine if possible whether this accounts for the inhibition.

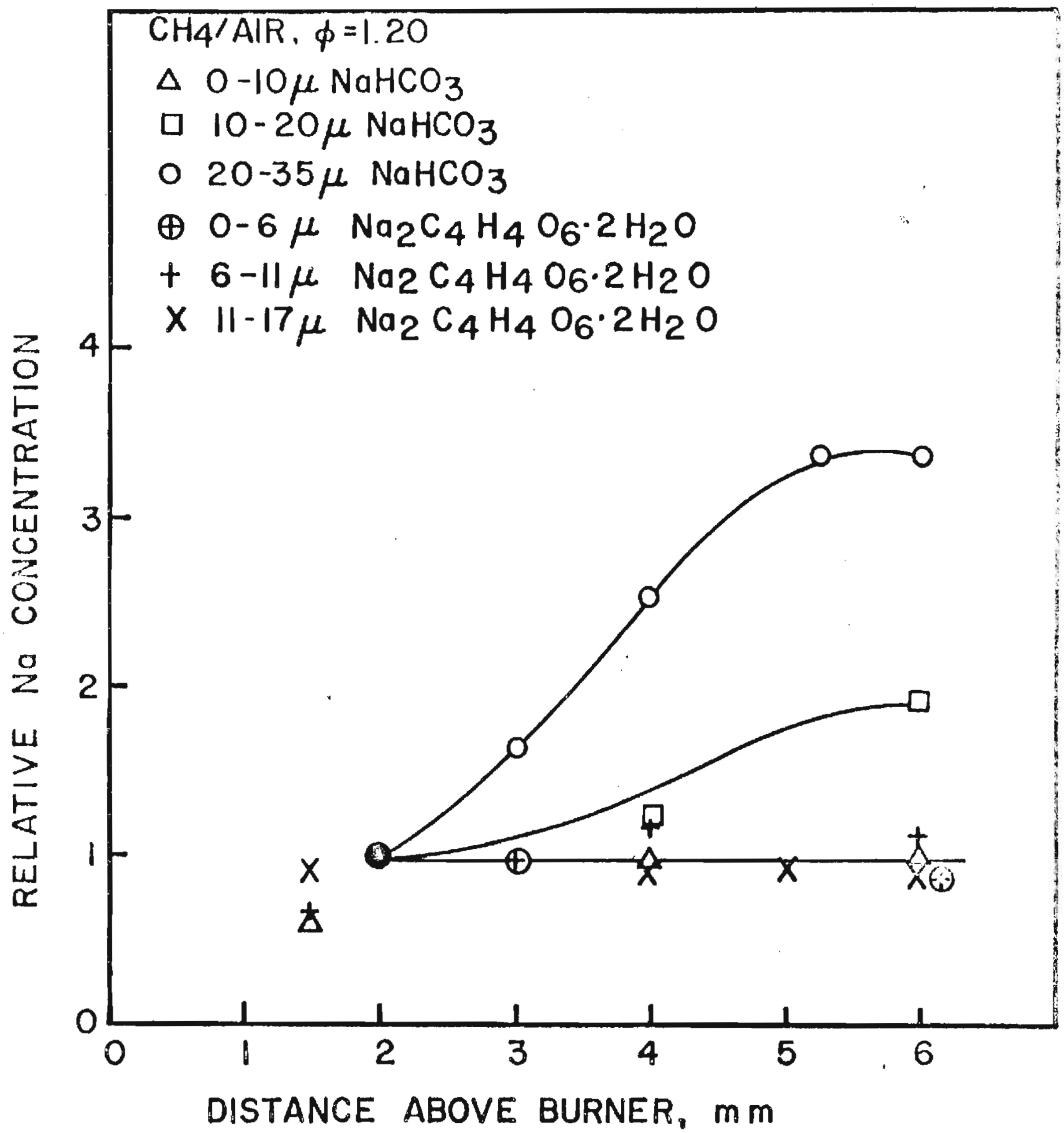
Reports:

1) "The Measure of the Inhibition of Quenched Premixed Flames", K. Sridhar Iya, Sue Wollowitz and Walter E. Kaskan Combustion and Flame, in press.

2) "The Mechanism of Flame Inhibition by Sodium Salts", K. Sridhar Iya, Susan Wollowitz and Walter E. Kaskan Submitted to the 15th Symposium (International) on Combustion.



CH4 / AIR , φ = 1.20
△ 0-10 μ NaHCO3
□ 10-20 μ NaHCO3
○ 20-35 μ NaHCO3
⊕ 0-6 μ Na2C4H4O6·2H2O
+ 6-11 μ Na2C4H4O6·2H2O
X 11-17 μ Na2C4H4O6·2H2O
ΔT, °K
0
50
100
150
200
0
2
4
6
8
10
Na X 10-14, ATOMS/CC



CH4/AIR, φ=1.20
△ 0-10μ NaHCO3
□ 10-20μ NaHCO3
○ 20-35μ NaHCO3
⊕ 0-6 μ Na2C4H4O6·2H2O
+ 6-11μ Na2C4H4O6·2H2O
X 11-17μ Na2C4H4O6·2H2O
RELATIVE Na CONCENTRATION
DISTANCE ABOVE BURNER, mm
0
1
2
3
4
5
6

NORTHWESTERN UNIVERSITY

SUMMARY FORMAT

NSF/RANN Conference on Fire Research

Institution: Northwestern University NSF Grant No.: GI-36761

Grant Title: Behavior of Water Droplets in Fire Plume

Principal Investigator: M. C. Yuen, ME/AS Department, Technological Institute
Northwestern University, Evanston, Illinois 60201
Phone: (312) 492-5647

Other Professional Personnel: Kenneth Dale, Graduate Student

Project Summary:

In the extinguishment of fire, it is generally agreed that the most effective way in the use of water is the direct wetting and cooling of the burning combustibles themselves. For this to happen the terminal velocity of the droplet must be larger than the velocity of the rising fire plume. In the case of high intensity fire, the velocity of the rising fire plume can be 30 ft/sec or above at the flame tip. The terminal velocity of the largest water droplet ($D \sim 7$mm) which will not break up is about 30 ft/sec in ordinary atmosphere.

In the fire environment, the most important factor which will influence the terminal velocity is evaporation. It has been shown that evaporation reduces drag thus increases the terminal velocity. On the other hand evaporation will also reduce drop size thus ultimately reduce the terminal velocity.

The objective of this research is therefore to study quantitatively the drag and heat transfer of water droplets when evaporation is important. We would also investigate the effect of changing the properties of water by chemical additives to increase its ability to penetrate a fire plume.

In this case the fire plume is simulated by a vertical wind tunnel with a 3" x 3" test section 12" long. It has a capability of a static temperature of 1000°C and a velocity of 40 ft/sec. Photographic method will be used to record the time history of the diameter of the droplet in the wind tunnel. The drag and heat transfer rate can then be deduced from the data.

Progress Report

Since last summer, the three components of the experiment; 1) hot air tunnel, 2) droplet release device, 3) photographic equipments have been calibrated and synchronized. It was found during the initial experiment that the droplets tend to wander to the side thus limiting the test time and affecting the accurate measurement of drop sizes. It turns out to be extremely difficult to control the side motion of a droplet in a high temperature wind tunnel. The final solution is to minimize the side motion as best as we can and to increase the depth of field of the optical system so that the droplet would still be in focus away from the axis of the wind tunnel. The final design allows a test time of about 1/4 to 1/2 second with the lens system having a f/number of 45.

So far water droplet data has been taken with droplet sizes from 3.5 mm to 4.9 mm and temperature from room temperature to 550°C. These together with the data from Eisenklam, Lane and Green are plotted in Figure 1. Presently we would like to extend our data to lower Reynolds number and higher temperature. Other liquid especially with lower heat of vaporization would also be used to correlate the heat transfer data.

Accomplishments

(1) Wind tunnel, droplet release device, photographic system have been calibrated and synchronized.

(2) Drag data of water droplets at Reynolds number of 1000 to 2000 have been measured.

Potential Applications

The knowledge gained in this study would allow a designer to quantitatively predict the chances of a particular size droplet to penetrate a given fire plume. This in turn would allow him to better design a sprinkler system or other delivery system.

Future Milestones

(1) Continue drag measurement to lower Reynolds number and higher temperatures of water droplets and other liquids.

(2) Heat transfer measurement of water droplet and other liquids with lower heat of vaporization to establish the correlation of Nusselt number with Reynolds number, Prandtl number and mass transfer number.

(3) Effects of chemical additives on break-up and evaporation of droplet.

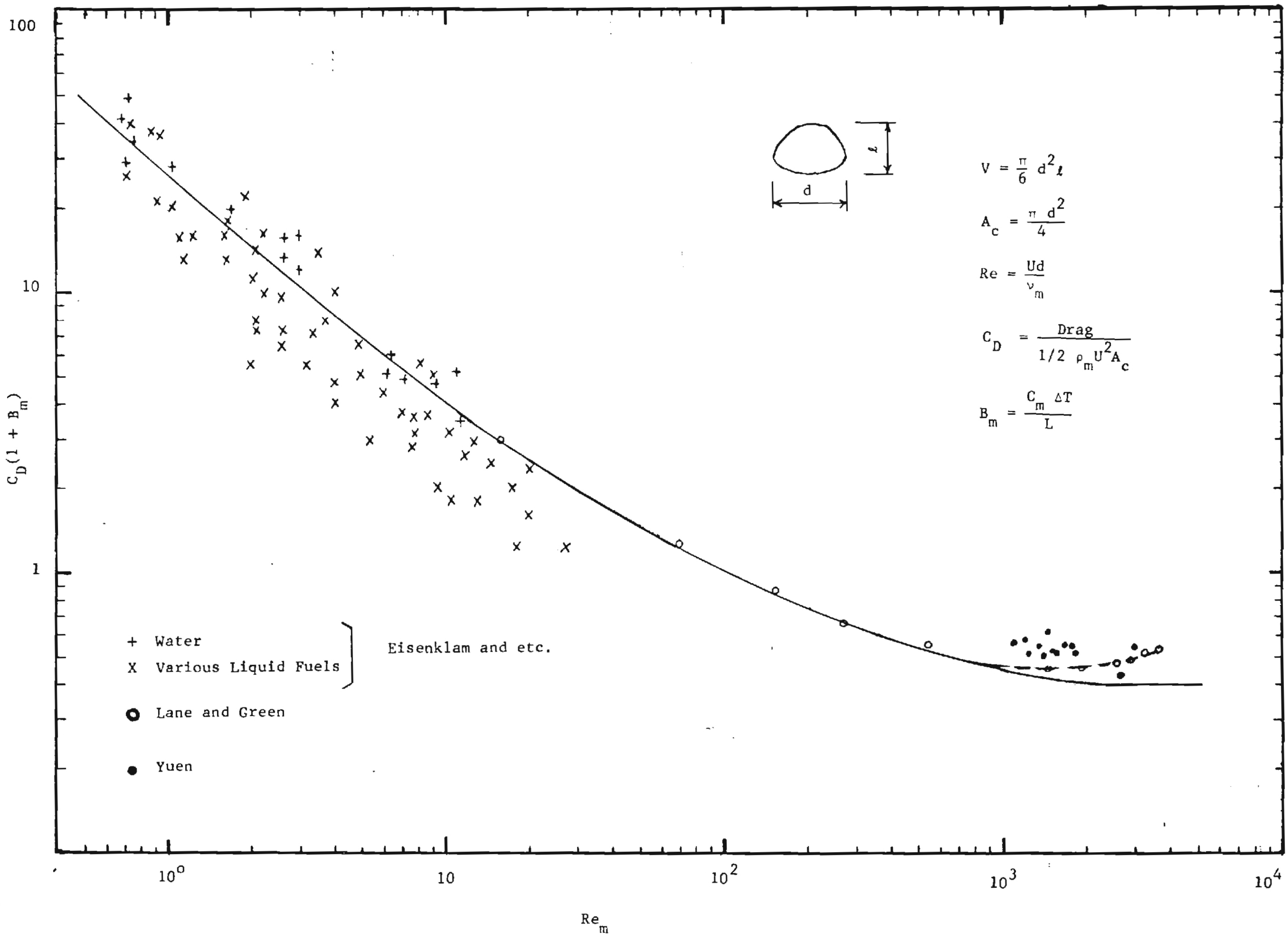


Fig. 1 Drag coefficients for evaporating drops in air.

Institution: University of Washington — NSF Grant GI 36528X

Subgrants to: University of California, San Diego, and Washington State University

UNIVERSITY OF WASHINGTON

Grant Title: Mechanisms of Wildland Fire Suppression

Principal Investigator

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Other Professional Personnel

Univ. of Washington

- C.A. Depew, Faculty Associate
- T.I. Yu, Graduate Student

University of California, S.D.

- F.A. Williams, Principal Investigator (UCSD Component)
- J. Kent, Postdoctoral Research Engineer
- S. Ubhayakar, Postdoctoral Research Engineer
- K. Seshari, Graduate Student

Washington State University

- D.T. Pratt, Principal Investigator (WSU Component)
- D.E. Stock, Faculty Associate
- C.J. Chung, Graduate Student
- M. Chung, Graduate Student

Project Summary

The objective is quantitative modeling capability for direct suppression of wildland fires. Of particular interest are critical conditions, such as break-out beyond initial attack status, salient penetration of major fire lines, or concentrated defense of valuable property. Quantitative understanding of fire response under such conditions will assist in optimal deployment of wildland fire-fighting resources, and in the evaluation of proposed fire-attack tools (e.g., dramatically expanded aerial capability) for which empirical performance information is lacking. The specific task of the work supported by the present grant is to formulate and develop appropriate models insofar as possible on the basis of analysis and laboratory-scale experiments, and to design meaningful field-scale experiments, including appropriate instrumentation.

On the basis of consultations with the USDA Forest Service, realistic wildland fire scenario descriptions have been established for critical fires in Southern California brush, a Northern Rocky Mountain forest, and Pacific Northwest douglas fir mixed slash and old-growth forest. Parameters for suppression models are derived from these descriptions. Important parameters are fuelbed size distribution and configuration, and length scale of coordinated flame phenomena ($\sim$10 m).

Suppression models must describe quasi-steady fire intensity and its modification by suppressive action, and extinction. Local extinction can contribute to intensity reduction on a larger scale. The fundamental approach to modeling is based on thermal coupling between the fuelbed and the gas phase flames. The fuelbed gasifies in response to thermal attack. The flame configuration, and hence the thermal attack, depend primarily on the gasification rate.

In this work, fuelbed response is being investigated at the University of Washington, and work on gas-phase phenomena and overall system modeling at University of California, San Diego. Each effort constitutes about 40 percent of project total. At Washington State University, field-scale experiments are being designed, at approximately 10 percent total project effort. The approximately

10 percent effort remaining is devoted to project coordination, both internally and externally with the Forest Service, including quantitative problem definition on the basis of fire scenarios.

Progress Report

1. Fuelbed Response. Experimental apparatus simulating the gross fire environment (primarily radiation), together with suppressant application (water spray, so far) has been developed and is being used to study response of approximately 30 x 20 cm fuelbed samples. Primary effort to date has been devoted to boards of douglas fir, pine, and oak. Such quasi-one-dimensional fuelbeds are amenable to reasonably complete theoretical analysis, with a useful existing foundation (e.g., Kung and Kalelkar, Combustion and Flame, 20 1 (1973) 91). Our intent is to extend the work to more realistic fuel samples, such as pine needle beds, bundles of brush, or assortments of logging slash debris. At present, however, the one-dimensional work is not quite complete. Time-consuming problem areas, now resolved, were thermophysical properties of char and wood, and water spray characteristics and control.

2. Gas-Phase Extinction Phenomena. A Damköhler number criterion for gas-phase extinction has been derived and checked experimentally for a series of small-scale laminar flow systems. Work with cellulosic fuels, and with water spray application, is in progress.

3. Overall Model Development. Complete overall fire model requires, in addition to fuelbed response, a description of fire behavior as a function of fuel gasification. The most critical aspects of fire behavior are those which determine heat transfer to single fuel elements. The framework of a phenomenological model contining such a description has been formulated. Standard engineering heat transfer relations are exploited wherever possible, in a manner appropriate to the extent of coordinated flaming. Results derived from experience, and partially justified by rough theory, determine the extent of coordinated flaming as a function of fuel gasification flux. It is noted that field-scale experimentation will be required to refine the model.

4. Design of Field-Scale Experiments. Measurement requirements for field-scale experiments have been defined. Most of the high priority measurements can be obtained by established, in situ methods. A tradeoff, taking into account these requirements, as well as a careful engineering analysis of remote sensing technology, indicates that the only remote instrumentation justifiable in the near term is a laser Doppler velocimeter. A lidar system could provide information of greater value, but at a difficult-to-justify cost and considerable development time.

Accomplishments (See Progress Report)

1. Realistic fire scenarios established.
2. Fuelbed response simulator in operation.

Potential Applications (See Project Summary for long term applications)

1. Laboratory evaluation of retardant and thermal resistive coatings.
2. Further quantification of Rothermels intensity I in Forest Service rate-of-spread model.
3. Development of revised fire protection criteria for logging slash disposal burning.

Future Milestones

1. Complete burning board investigation - July 1974.
2. Complete experiment with realistic wildland fuelbed samples - October 1974.
3. Damköhler number extinction criteria applied to cellulosic fuel samples - July 1974.
4. Quantify influence of water spray on physico-chemical constant in theory as applied to laboratory-scale phenomena - August 1974.
5. Complete overall model for intensity control by suppression action - September 1974.
6. Preliminary definition of field-scale experiments - June 1974.
7. Detailed design of field-scale experiments - November 1974.

Reports and Publications

Comprehensive Semi-Annual Reports, Submitted to National Science Foundation, August 27, 1973 and January 18, 1974.

L. Krishnamurthy and F.A. Williams, "Diffusion Flames at the Stagnation Point of a Condensed Fuel," Paper WSCI 73-10, 1974 Spring Meeting, Western States Section/The Combustion Institute, Arizona State University, Tempe, Arizona (16, 17 April 1973).

R.C. Corlett, "Wildland Fire Suppression: A Combustion Science Overview," Paper WSCI 73-12, 1973 Spring Meeting, Western States Section/The Combustion Institute, Arizona State University, Tempe, Arizona (16, 17 April 1973).

R.C. Corlett, C.A. Depew and T.I. Yu, "Toward a Unified Fire Suppression Criterion," Paper WSCI 73-22, 1973 Fall Meeting, Western States Section/The Combustion Institute, The Aerospace Corporation, El Segundo, California (29, 30 October 1973).

C.A. Depew, R.C. Corlett, T.I. Yu, G.A. Cruz, "Response of Wood Boards to Radiative Heating and Water Spray," Paper 73-26, 1973 Fall Meeting Western States Section/The Combustion Institute, The Aerospace Corporation, El Segundo, California (29, 30 October 1973).

D.E. Stock, C.R. Corlett and C.A. Depew, "Instrumentation for Full-Scale Fire Suppression Experiments," <u>Experimental Methods in Fire Research Meeting</u>, Stanford Research Institute, Menlo Park, California (9, 10 May 1974).

F.A. Williams, "A Unified View of Fire Suppression," <u>J. Fire and Flammability</u> <u>5</u> (January 1974) 54.

J.H. Kent and F.A. Williams, "Extinction of Laminar Diffusion Flames for Liquid Fuels," <u>Fifteenth Symposium (International) on Combustion</u>, Tokyo, Japan (August 1974).

SUNY AT
STONY BROOK

NSF/RANN Conference on Fire Research

Institution

State University of New York at Stony Brook

NSF Grant No.

GI 37201

Grant Title

A Study of the Role Played by Fire Whirl and Firebrand in Fire Storm Type Mass Fires.

Principal Investigator

Richard S. L. Lee, Department of Mechanics
State University of New York at Stony Brook
Stony Brook, New York 11794

Tel: 516-246-6771

Other Professional Personnel

Frank W. Otto (Graduate Student)
Philip J. Pritchard (Graduate Student)
George A. Greene (Graduate Student)

Project Summary

The "MASS FIRES", fires showing the more violent fire behavior, so commonly found in urban as well as wildland environment, has largely remained to this day one of the potentially most hazardous and technically least understood phenomena of immense social, environmental and economical importance. It has been recently recognized that in both the internal spread from the more intensely burning regions to the less intensely burning or unburned regions within the confines of such fires and the outward spread of such fires, the combination of flow vortex formation and firebrand activities plays an important role. Our objective is to obtain an understanding of this unconventional spread mechanism and to relate it to actual mass fire behavior particularly in an urban environment.

Progress Report

It should be particularly mentioned that there has been a major shift in the applicational orientation, although not in the basic substance, of our research effort from mostly leaning towards the forest and wildland fire environment to mostly leaning towards the urban fire environment as a result of our extended contacts with the National Fire Protection Association in Boston and the Department of Fire of the City of New York. This important shift has brought about added incentive and significance to the relevance of our investigation. Dr. Ralph Long's encouragement and help in this regard is hereby gratefully acknowledged.

A. Urban Conflagration Mass Fire

Our first direct contacts with the National Fire Protection Association in Boston came at a time shortly after the mass conflagration fire of historical proportion of Chelsea in that metropolitan area which occurred on October 14, 1973. The behavior of this fire was so violent and unpredictable that seventeen city blocks were consumed in just a few hours and perhaps only by sheer luck the rest of the greater Boston area escaped the holocaust. After a series of intensive interviews with fire fighting personnel and careful examination of slides, photographs, maps and thousands of feet of news movie films obtained from the various Boston television stations, together with records on an almost identical conflagration mass fire over practically the same city area of some sixty-five years earlier, a comprehensible picture on the development of that fire gradually emerged. A joint paper by R. S. L. Lee and A. R. Granito, Research Director of the National Fire Protection Association, gave an analysis to such items as the immensity of size of fire area, the fire load condition, the location of initial ignition point, the intensity of fire, the violent air movement and firebrand spotting and the rapid spread during main run. In this case the prevailing ambient wind had been consistently maintained at a very high level and there were abundant stocks of very high fire-loading substances both inside and outside the buildings and also in the building structures themselves, which could easily support a very strong sustained fire-plume, as well as abundant stocks of the kind of substances which would make the most effective firebrands. The complex interaction of spot fires in the initial three block fire area enhanced the establishment of a mass fire. The enormous sudden increase in rate of heat release there raised the previously severely inclined plume to a position of thrusting up nearly vertically for many thousands of feet before giving in to the strong prevailing ambient wind. The interaction between these two flow fields produced in the wake region of the plume such unusually high levels of wind speeds as typically those associated with the shedding vortex, or fire-induced tornado, which are adequate to transport burning firebrands rapidly to much of the rest of the 17-block fire area to initiate large numbers of additional spot fires. These new spot fires in turn grew in size to eventually engulf and quickly consume the entire fire area. During the week of March 10, 1974, a very similar conflagration mass fire burned down fourteen whole residential city blocks in Caracas, Venezuela, also within rather short time in an almost identical fashion.

B. High Rise Building Fires

Our exposure to the phenomenon of the high rise building fires through our timely contacts with the Department of Fire of the City of New York has brought a new dimension and impetus to our study on vortex flows in a fire environment. This Department of Fire has a personnel size of over 15,000, of which about 13,000 are firemen, with jurisdiction over all five boroughs, of the City. Numerous meetings have been held between R. S. L. Lee and such key officials of the Department as Mr. John T. O'Hagan, Commissioner of Fire and concurrently Chief of Staff, Mr. Sidney Ifshin, Deputy Chief of Staff, and Mr. Homer G. Bishop, Deputy Assistant Chief in charge of the Division of Planning and Operations Research (Pandor). Commissioner O'Hagan and Chief Ifshin are probably two of the foremost experts in the country in high rise building fires. (As a matter of fact, Commissioner O'Hagan has just come back recently from an inspection trip to Sao Paulo, Brazil, to examine the most recent, spectacular high rise building fire in that city.) Chief Bishop has under his control the operational fire information over the largest and easily the most important conglomeration of high rise buildings in the world. At these meetings, these officials expressed a strong and earnest interest in collaborating with us in the study of smoke, air and fire movements, both exterior and interior, in high rise structures and other urban fire problems. They also offered to extend to us whatever assistance we might need within the resources of the Fire Department of the City of New York. Perhaps most important of all is their enthusiasm in the participation in the charting of the course of our research direction on a continuing basis.

One of the most common and effective ways of evacuating civilians from a high rise building on fire is the use of helicopters on the rooftop. This seemingly simple and safe procedure in most cases of actual fire situations has proved extremely complicated and dangerous due to the usually violent and unpredictable air movements around the building. This was the case, according to Commissioner John T. O'Hagan, in the most recent Sao Paulo, Brazil, high rise building fire in which the helicopter pilots had to fly around the fire area for over an hour and a half before successfully landing, with great risks, on the rooftop to pick up the hundreds of waiting occupants. By that time, many of those waiting on the rooftop had already plunged to their death. Ironically, the same thing happened in another high rise building fire in the same city a few years ago. From this point of view, it is of paramount importance to have a comprehensive understanding of these air movements.

A number of major high rise building fires present a rather peculiar fire behavior. One example is the August 5, 1970, fire in One New York Plaza, a new, 50-story, office building in New York City. It spread from the point of origin on the 33rd floor to the 34th floor and involved an area of approximately 20,000 square feet on each floor. Structural damage was extensive and the contents were almost completely incinerated. Two occupants lost their lives and many others were seriously injured. The results of this fire were particularly disturbing because high rise buildings are not supposed to allow fire to extend vertically from floor to floor, or horizontally from one compartment to another. These results were intimately related to the air movements inside the building. Basically, whenever a temperature differential exists between the interior and exterior of an enclosure, a phenomenon known as stack or chimney effect prevails. When the interior temperature is higher than the exterior, there is normally an inflow of cold air at low levels and a corresponding outflow at high levels. However, these air flows will be greatly effected if there are significant air movements outside the building. Hence, from this point of view also, it is of paramount importance to have a comprehensive understanding of these external air movements.

The external air flow around a high rise building on fire is usually not a very simple matter. However, it is related to the hot buoyant free-convection plume associated with the fire and internal heating of the building and the prevailing ambient wind in an intertwined fashion. Even if without ambient wind, the free convection flow above a circumferencial heat source is an extremely complicated one--the most recent Sao Paulo fire seems to give such an appearance due to extensive external spread of fire. Both these sources of air movements induce air movements external to the building. The interaction between strong prevailing ambient wind and combination of the body of the building and the thermal plume above can usually produce violent vortex air movements in the neighborhood of the building. The induced air flows when influenced by the arrangement of surrounding building and street patterns can also produce violent vortex air movements in the neighborhood of the building. Furthermore, the external air movement outside the building has a dominate effect on the internal movements of smoke, hot gas and fire inside the building through openings such as broken windows, opened doors, vents from smoke shafts, etc. It is the violent vortex motion of air that deserves special attention in the study of external air movements of high rise building fires.

Accomplishments

A. Gross Vortex Activities in a Simple Simulated Urban Fire

An experiment has been conducted on an originally seemingly inconspicuous burn in a simple simulated urban street arrangement, as shown in Figure 1, which is inducive to probable gross vortex formation. The results reveals in vivid details a series of most unusual and exciting events of gross vortex development and their related firebrand spotting activities, as shown in Figures 2 through 8. Quantitative determination, in terms of the value of the non-dimensional parameter Froude number, as shown in Figure 9, of the points of demarcation of these events has been facilitated by the comparison of results of two burns of mere geometrical similarity, as shown in Table 1. These findings point to a promise of an understanding of, among other things, some of the strangest fire behaviors observed in large urban fires.

A paper on the results and conclusions of this work will be presented at the Fifteenth International Symposium on Combustion, Tokyo, Japan, August 25 - 31, 1974.

B. Vortex Formation Behind a Strong Plume in a Strong Prevailing Cross Flow

We have gained much more insight into the phenomenon of periodical vortex shedding in the wake of a flow past a strong cross jet or plume. The information which we have obtained so far, from both the hydraulic simulation using two-dimensional laser-Doppler anemometry in our laboratory and the evidence gathered on some recent large-scale mass fires, gives a vivid description of this extremely interesting phenomenon. The first evidence of occurrence of such a phenomenon in a large scale fire was discovered in the viewing of a series of slides taken of the plume of the "Granite Fire" running over many square miles in relatively short period of time in the Stanislaus National Forest adjacent to the Yosemite National Park in northern California on August 17 - 21, 1973. On a smaller scale but in an urban environment, the same phenomenon was observed in a spectacular urban fire in a heavily populated residential area in Nesconset on Long Island, New York, about four miles from our campus, in the late afternoon of July 20, 1973. The first evidence of occurrence of this phenomenon in a large-scale urban fire was discovered in the viewing of slides, photographs, maps and thousands of feet of news movie films obtained from the various Boston television stations of the Chelsea mass conflagration fire of October 4, 1973.

A paper on the study is currently prepared for publication.

Potential Applications

Conflagration mass fires in urban areas have occurred in increasing frequency in recent years for a number of reasons. First, the three decades since the end of the second world war have witnessed the unprecedented growth of urban areas surrounding the major city centers of the world in general and of the United States in particular. Secondly, the almost universal rapid deterioration of the big cities, particularly those in this country, has turned these same urban areas into potentially the most probable places for the deadly conflagration mass fires to blow up. Thirdly, people dealing with either fire prevention or fire fighting usually find themselves rather helpless in confronting a holocaust of this order of magnitude due to a lack of sufficient understanding of the internal workings of such a dramatic phenomenon. As a consequence, the ordinance and building codes of most such communities are not adequate enough to cope with the potential of occurrence of conflagration mass fires. Many urban areas have gone through this kind of disastrous experience once or even more than once. Many others have narrowly avoided having some of their ordinary fires transformed into mass fires. Still many others have been sitting on top of literally many square miles of distributed dynamite without knowing it. In New York City alone, one can easily cite numerous such areas. For instance in residential areas, there are the Flushing and Rockaway section in Queens, the Bushwick section in Brooklyn and the Bulls Head section in Staten Island. In industrial areas, there are the Southern Queens section adjacent to the John F. Kennedy International Airport, the waterfront dock section in Brooklyn and the western part of Staten Island. Many similar areas can also be found in other parts of the greater metropolitan New York area of Long Island, Westchester County, northern New Jersey and western Connecticut. The situation, as bad as it is, will become even much worse due to the expected change in life pattern forced upon us by the energy crisis. With the rising cost and scarcity of fuel, more people will be drifted back to the city areas. Therefore, the potential danger of conflagration mass fires for these areas will be greatly increased and the potential extent of destruction in terms of both human lives and property will also be greatly increased. The urgency of finding a better understanding of the conditions contributing to the mysterious initiation of urban mass fires is quite obvious.

Future Milestones

The activities of the future depend to a great extent on the activities currently underway. However, in the area of simulated urban fire environment, the introduction of the height of street buildings as a parameter seems to be in order.

Reports

1. Lee, S. L. and Granito, A. R.: "Research Analysis-Conflagration Fire Behavior, The 1973 Chelsea, Massachusetts Fire", Fire Command, Vol. 41, No. 3, pp. 12-14, 1974.

2. Lee, S. L. and Otto, F. W.: "Gross Vortex Activities in a Simple Simulated Urban Fire", accepted for presentation, the Fifteenth International Symposium on Combustion, Tokyo, Japan, August 25-31, 1974.

3. Lee, S. L. and Hellman, J. M.: "Heat and Mass Transfer in Fire Research", invited chapter, Advances in Heat Transfer, Vol. 10, Academic Press, pp. 219-284, 1974.

4. Einav, S. and Lee, S. L.: "Measurement of Velocity Distributions in Two-Phase Suspension Flows by the Laser-Doppler Technique", Reviews of Scientific Instrument, Vol. 44, No. 10, pp. 1478-1480, October 1973.

5. Einav, S. and Lee, S. L.: "Particles Migration in Laminar Boundary Layer Flow", International Journal of Multiphase Flow, Vol. 1, pp. 73,88, 1973.

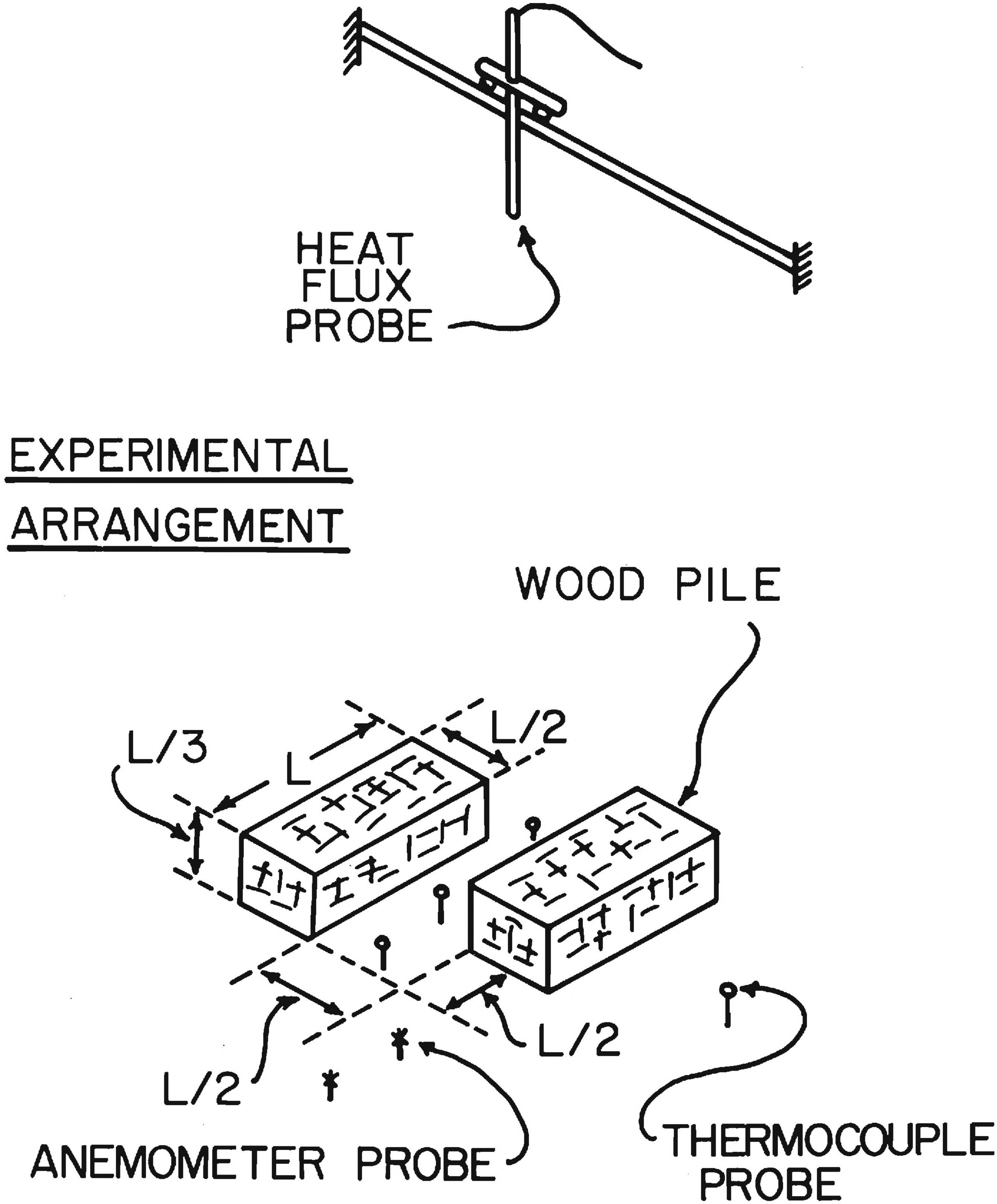
6. DiGiovanni, P. R. and Lee, S. L.: "Impulsive Motion in a Particle-Fluid Suspension Including Particulate Volume, Density, and Migration Effects", Journal of Applied Mechanics, Vol. 41, Series E No. 1,pp. 35-41, March 1974.

7. Garris, C. A. and Lee, S. L.: "An Instability of Shear Field-Buoyancy Field Interactions Leading to Vortex Formation", Journal of Applied Mechanics, in print 1974.

8. Garris, C. A. and Lee, S. L.: "A Theory for Multiple Fire Whirl Formation", The Fourteenth International Symposium on Combustion, pp. 1063-1071, 1973.

9. Lee, S. L. and Pritchard, P. J.: "Vortex Shedding from Turbulent Jet in a Cross Flow", in preparation for publication, 1974.

LIST OF CAPTIONS


HEAT
FLUX
PROBE
EXPERIMENTAL
ARRANGEMENT
WOOD PILE
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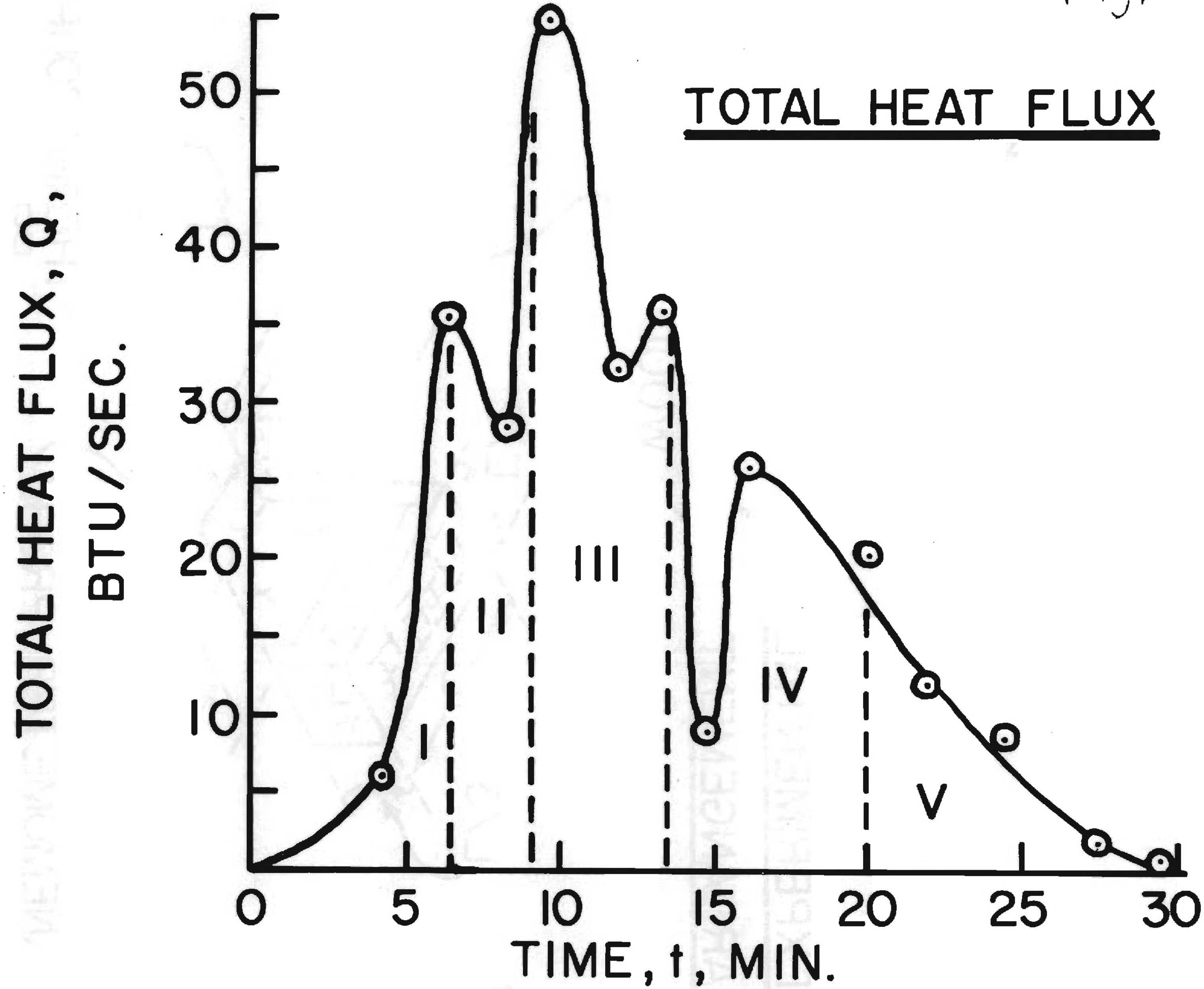
L/2
ANEMOMETER PROBE
THERMOCOUPLE
PROBE

Fig. 2


TOTAL HEAT FLUX
TOTAL HEAT FLUX, Q,
BTU/SEC.
TIME, t, MIN.
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15
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25
30
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I
II
III
IV
V

<u>STAGE I</u>

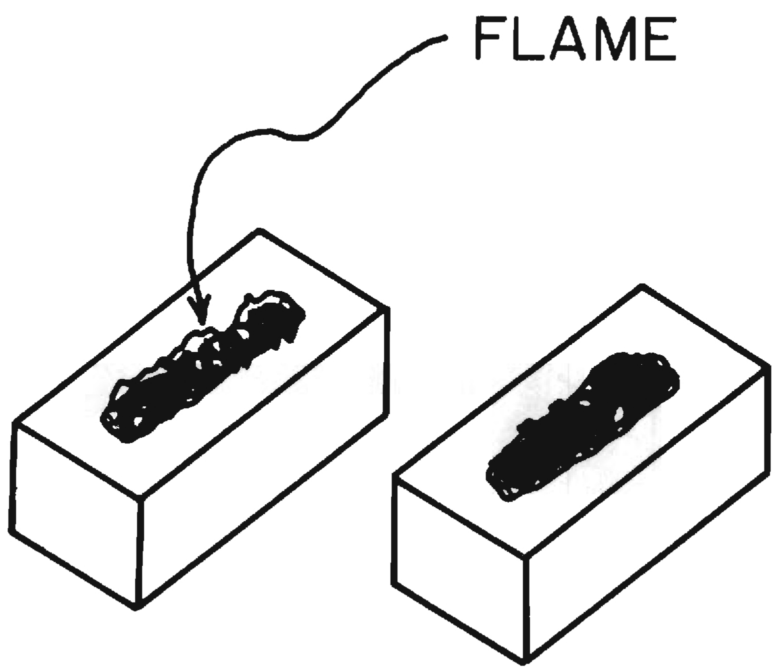
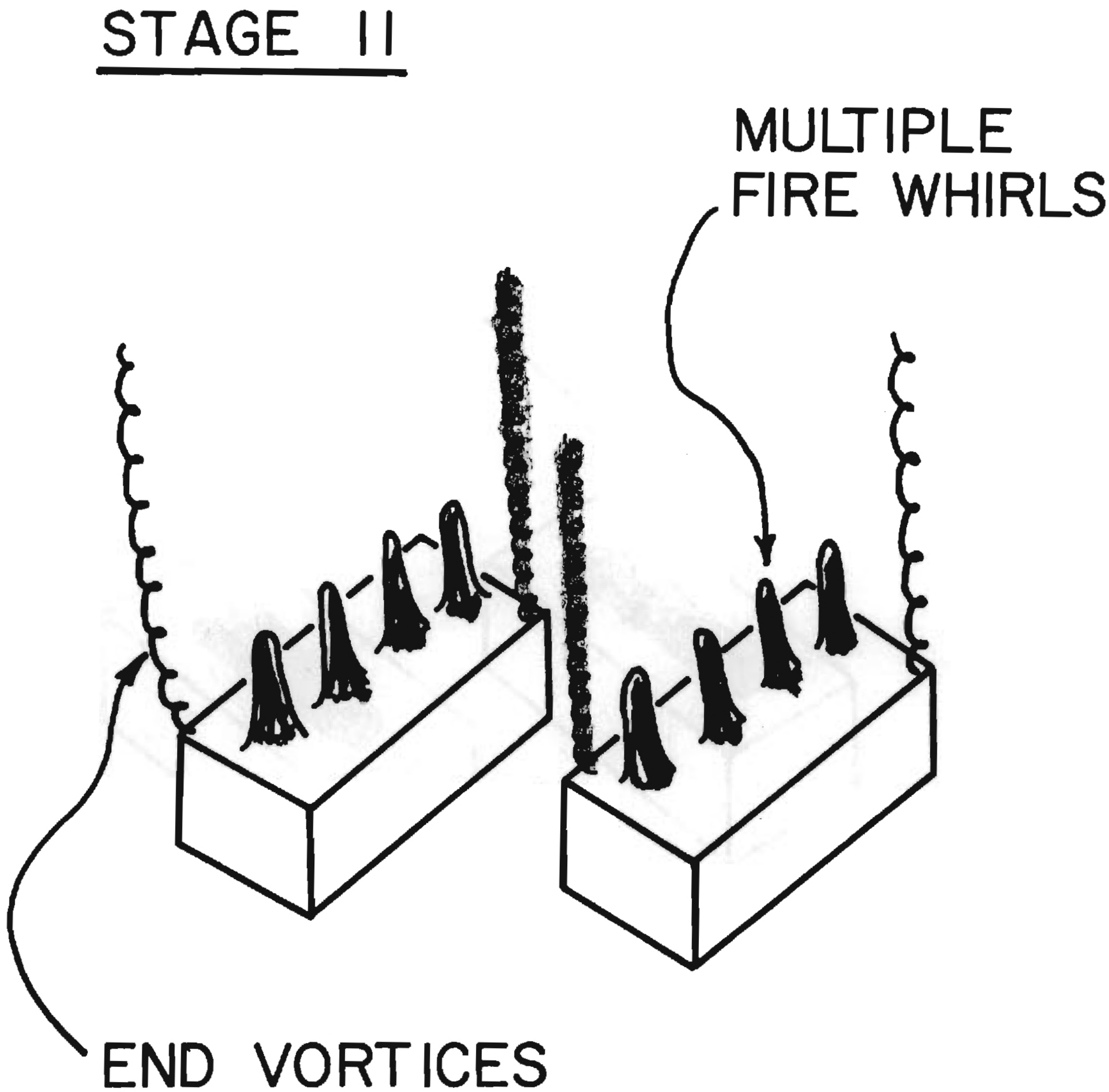


Fig. 4



STAGE III

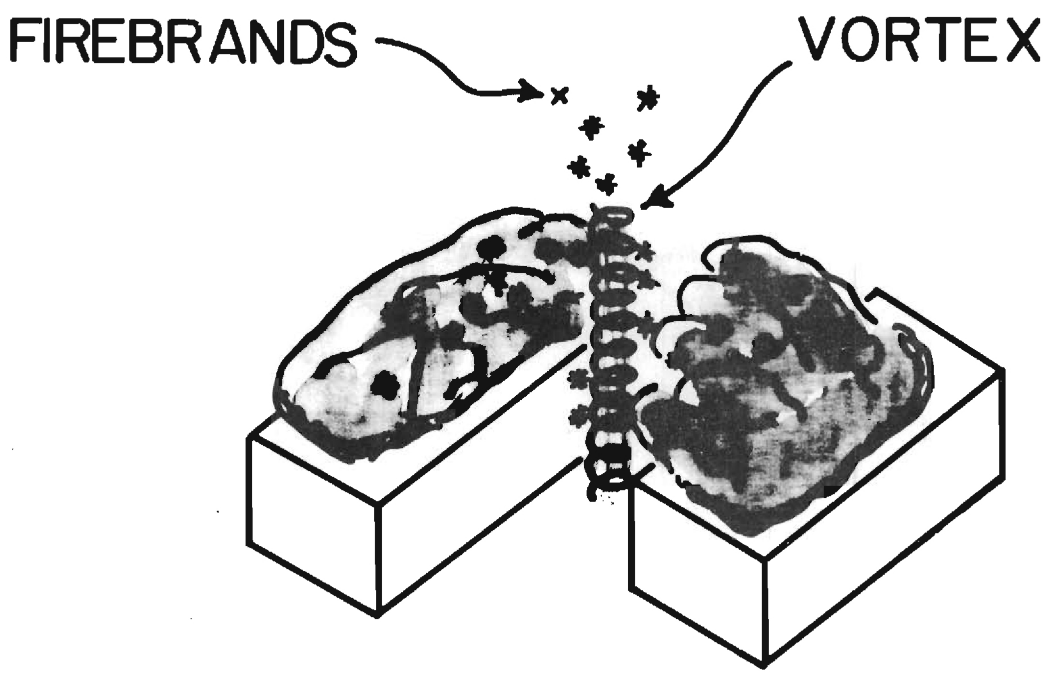
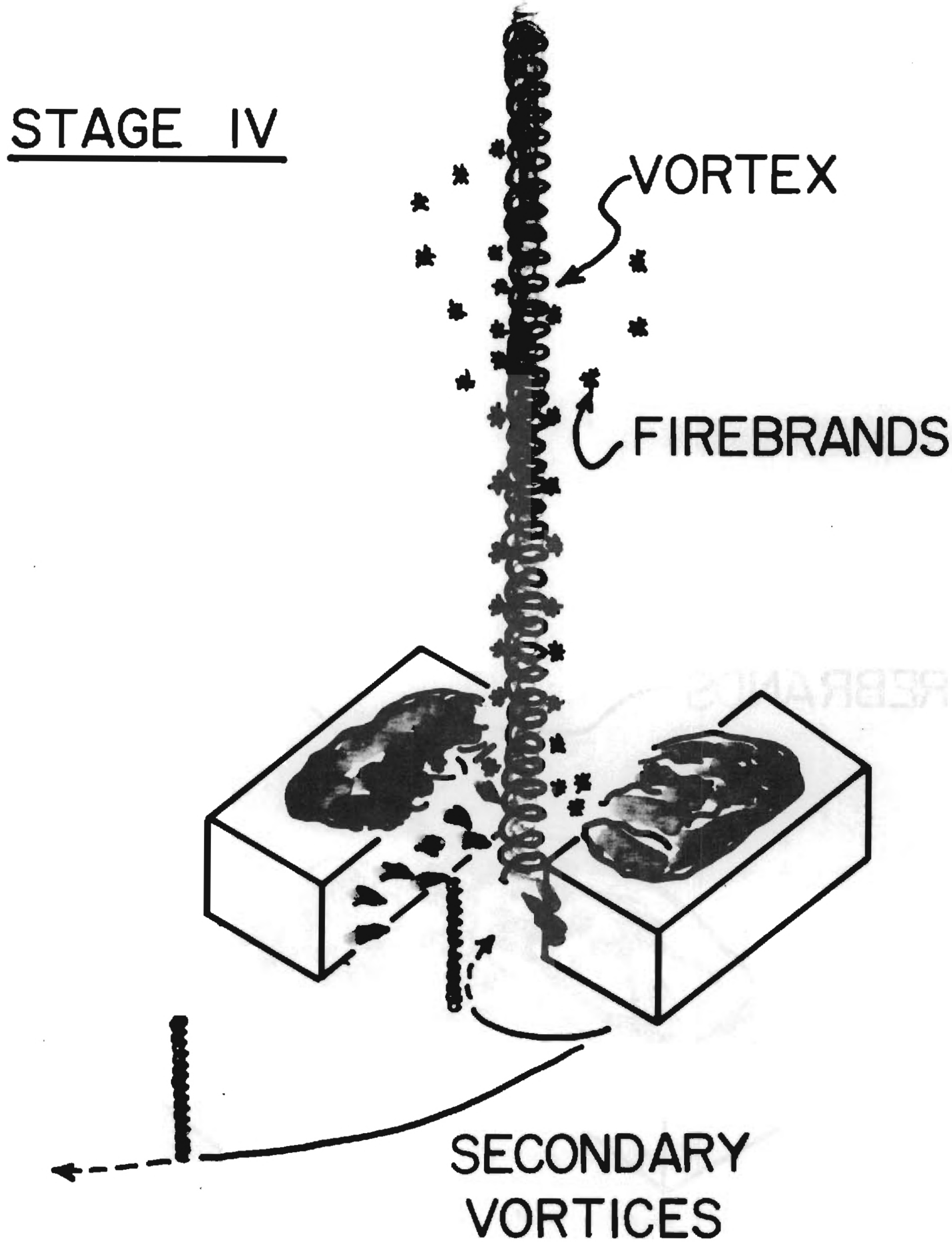


Fig. 6



STAGE V

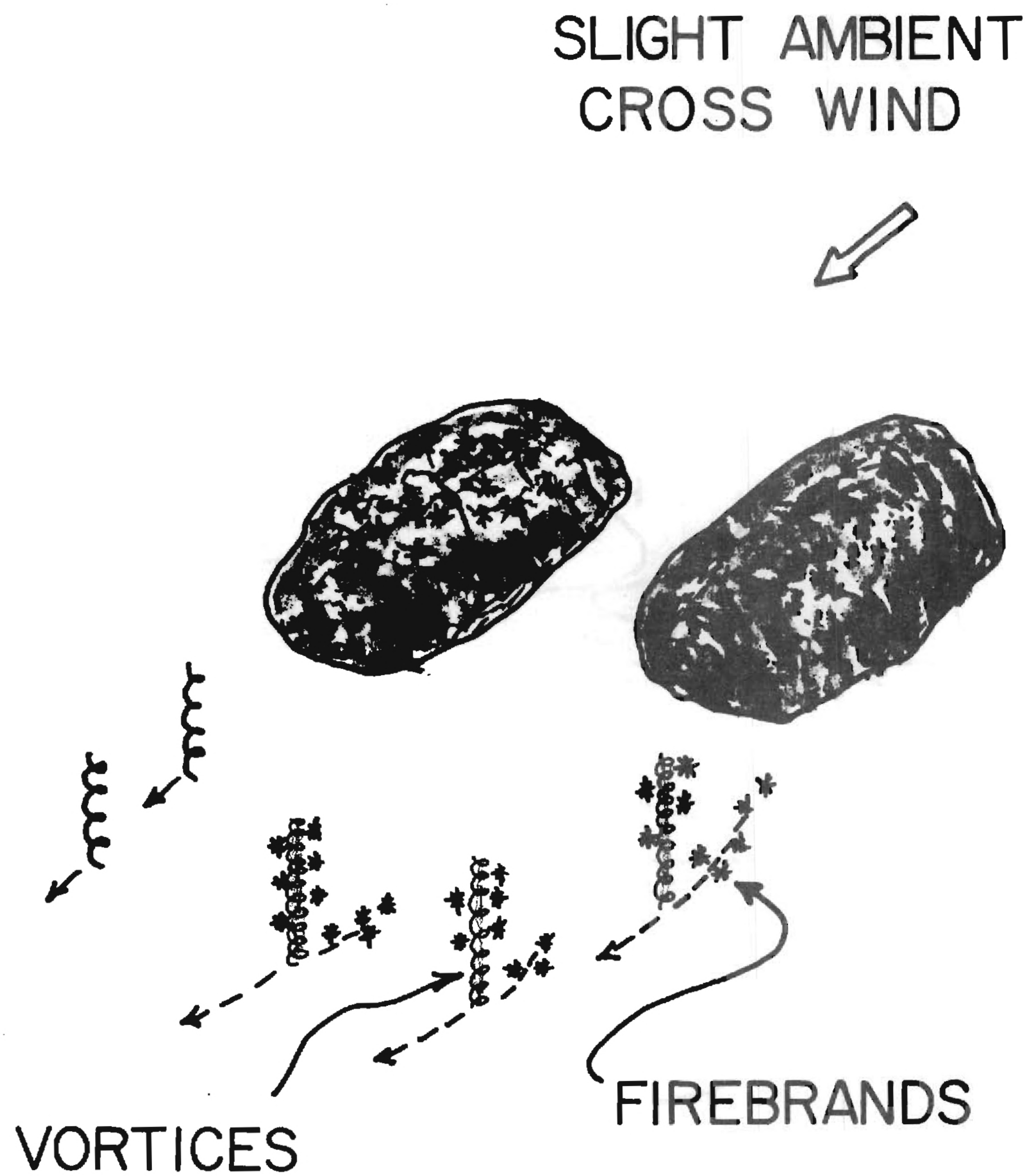
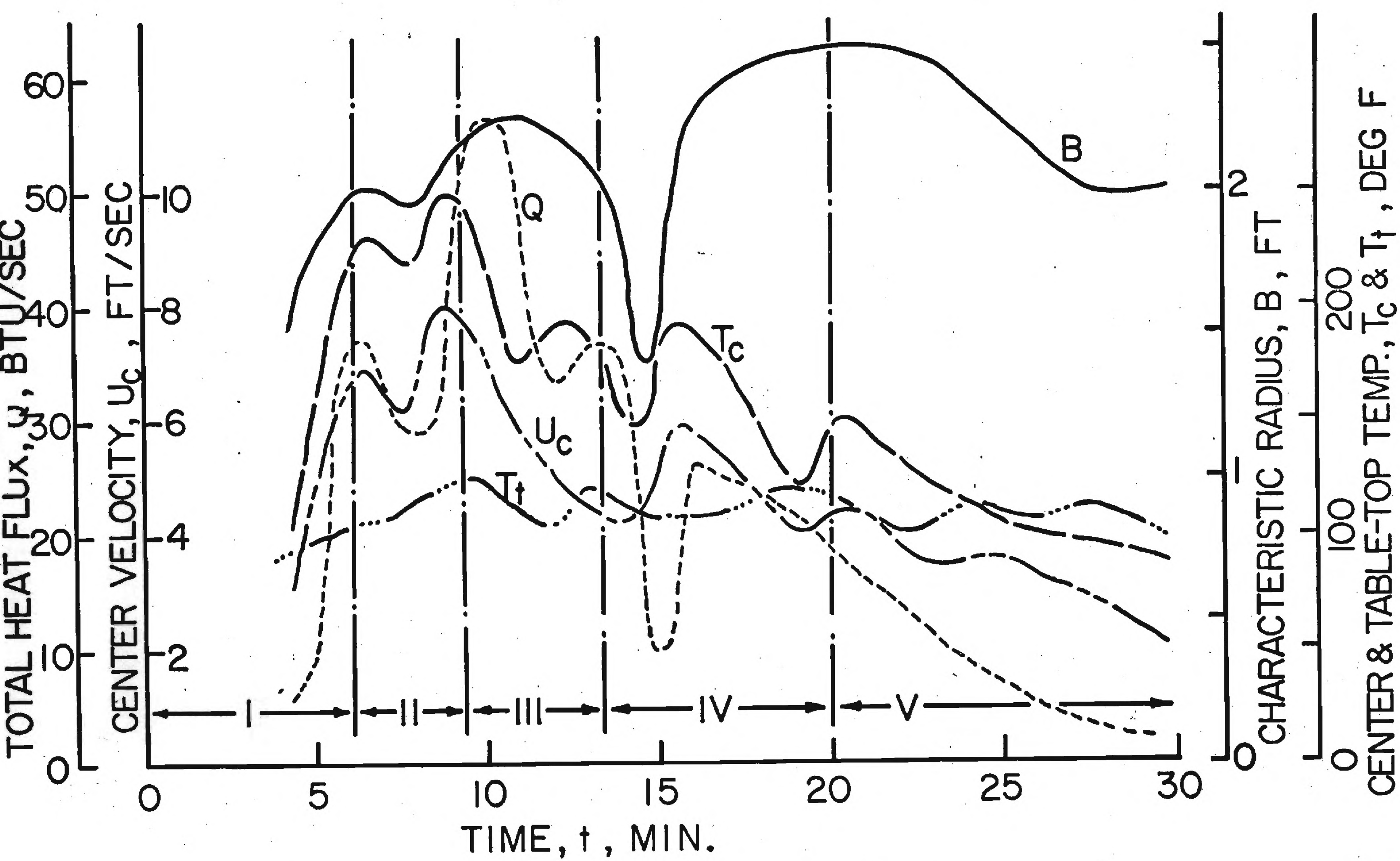


Fig. 8


TOTAL HEAT FLUX, Q, BTU/SEC
CENTER VELOCITY, U_c, FT/SEC
CHARACTERISTIC RADIUS, B, FT
CENTER & TABLE-TOP TEMP., T_c & T_t, DEG F
TIME, t, MIN.
B
Q
T_c
U_c
T_t
I
II
III
IV
V

A CHARACTERISTIC VELOCITY

$$\bar{U} = \left[\frac{gQ}{2\pi L C_p \rho_1 T_1} \right]^{1/3}$$

FROUDE NUMBER

$$F_r = \frac{\bar{U}}{(gL)^{1/2}} = \frac{Q^{1/3}}{g^{1/6} L^{5/6} (2\pi C_p \rho_1 T_1)^{1/3}}$$

CHARACTERISTIC LENGTH	OBSERVED TRANSITION POINT (Q, BTU/SEC)			
L	I–II	II–III	III–IV	IV–V
2 FT	35 (F_r=0.542,	52 0.616,	35 0.542,	18.5 0.438)
1 FT	7 (F_r=0.565,	10 0.636,	16 0.743,	12 0.675)

Table 1

Institution University of California, Riverside NSF Grant GI-31891X

Grant Title Forest Fire Statistical Problems

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	C. A. Robertson		J. Schwartz
			H. Shaarawy
			S. Suhartono
			S. Thompson

Project Summary

The project objective is to conduct an investigation into statistical aspects of fires in California federal forests. The purpose of this is to obtain insight into the behavior and relative importance of various types of fires, relevant to the planning of efforts to minimize losses due to them. The work falls into two main parts: firstly, to put the mass of data about California forest fires (obtained from the U. S. Forest Service Forest Fire Laboratory, Riverside, and from other sources) into a usable form and check its internal consistency as much as possible; secondly, to perform various statistical analyses on the data.

Progress Report

As regards the collection and organization of the data, the main effort has been directed towards production of a master magnetic tape containing extensive and detailed information about all fires in California federal forests over the years 1960-9. Approximately 20,000 fires are involved, and 80 items are recorded for each fire, which another 34 items included for all except the class A (smallest) fires. We have information about the location, time, size and cause of the fire, all described in detail; about the mode of discovery, the attack forces at various stages of the fire; the terrain, both in respect of its topography and the nature of the fuel bed; and the damage caused at various stages of the fire. The quality of this data has been cross-checked whenever possible, and many of the items about which information is sometimes unreliable (such as, for example, the estimated starting time) have a code attached to indicate how reliable the particular piece of data is. Details of all 114 variables are contained in a code book. Further work has been directed to producing a large number of maps showing dates and locations of lightning fires.

Several kinds of statistical analysis of the data have been undertaken. These analyses involve not only the data mentioned above but also some even more detailed data on large fires, collected with particular concern for investigation of spread rates. In these studies of spread rates we examined the relationship between the rates and a number of predictive variables such as temperature, wind speed, angle to wind, slope, and so on. We also considered some variables which are not so easy to classify, such as the fuel bed content, and found that, as we should expect, when these variables are taken into consideration better predictions of spread rate can be obtained. Another study showed that for several kinds of fuel bed most of the spread takes place in less than six hours. These fuel beds include brush, grass, and mixed brush and timber. This raises the question of how to anticipate when the critical six hour burning period will occur.

Further work has been done on the relationship between rainfall and fires. The conclusion so far is that there is little statistical correlation between the amount and timing of rainfall and the numbers and intensity of forest fires, notwithstanding the common opinion that the extra vegetation induced by heavy rainfall should lead to more fires later.

The maps giving details of lightning fires are in process of being analyzed to investigate clustering patterns in space and time.

The data about sizes of fires has been examined in further detail since our last report, and further statistical techniques for the analysis of very long-tailed distributions are being developed.

Accomplishments and Potential Applications

See Project Summary and Progress Report.

Future Milestones

Further statistical analyses of the kinds described in the Progress Report are being carried out this summer and will continue into the fall. More work is being done to relate meteorological conditions to fire spread rates, and the investigation of clustering patterns for lightning fires will come to fruition later this year.

Reports and Publications

Analyses of Forest Fire Data in California, C. A. Robertson. Technical Report Number 11, Department of Statistics, University of California, Riverside, November, 1972.

The Correlation Between Rain and Forest Fires, L. T. Tran. Technical Report Number 13, Department of Statistics, University of California, Riverside, March, 1973.

A Statistical Fire Spread Model for Forest Fires, A. W. McMasters. Technical Report Number 14, Department of Statistics, University of California, Riverside, April, 1973.

Individual Statistical Fire Spread Models for Different Fuel Types, A. W. McMasters. Technical Report Number 18, Department of Statistics, University of California, Riverside, February, 1974.

Active Wildland Fire Spread During a Burning Period, A. W. McMasters. Technical Report Number 19, Department of Statistics, University of California, Riverside, February, 1974.

NSF/RANN CONFERENCE ON FIRE RESEARCH

California Institute of Technology NSF Grant No:

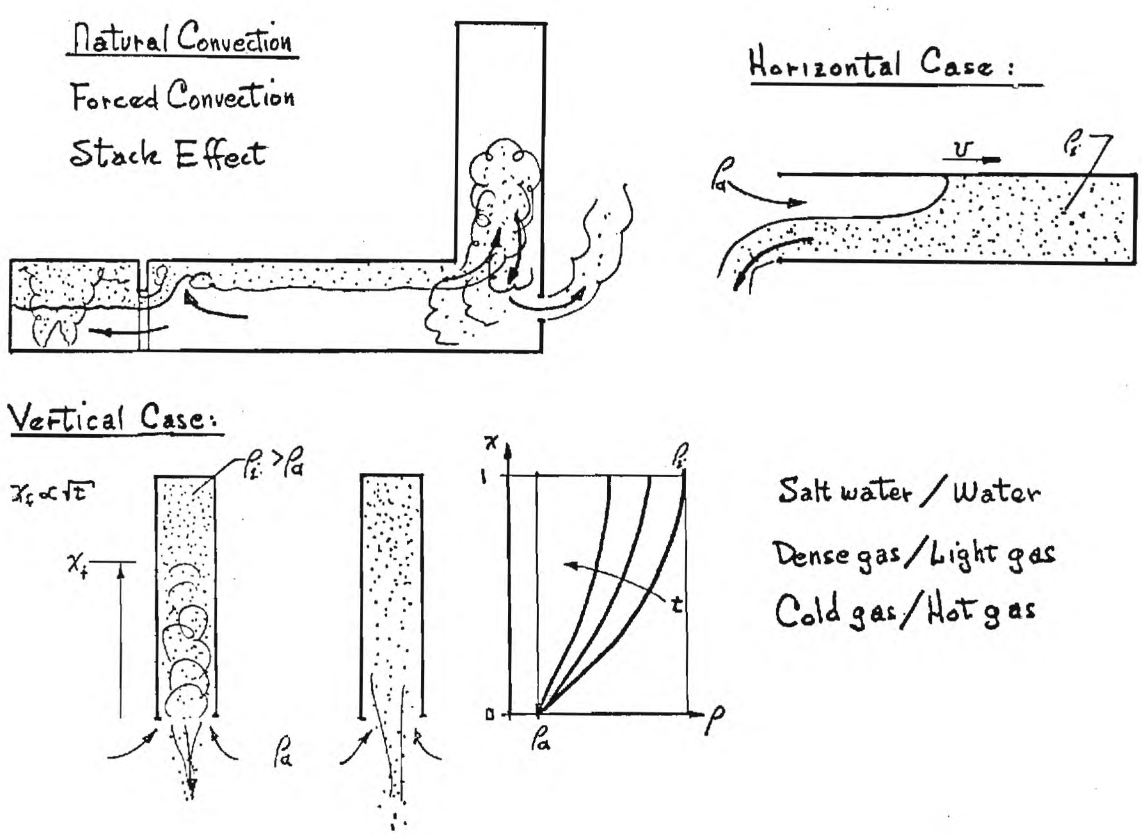
"Convective Flows under Conditions Applicable to Building Fires

Principal Investigator: Professor Edward E. Zukoski, Mail Stop 301-46, California Institute of Technology, Pasadena, California 91109; (213) 795-6811, ext. 1785

Other Professional Personnel: Mr. Johnnie B. Cannon, Graduate Student

During even a small uncontrolled fire in a building, large volumes of hot, toxic, and smoky gases are formed. The motion of these gases through the building will greatly influence the threat to life, the spread of the fire, and damage to building contents. Both natural convection and forced convection (due to stack effect or ventilation systems) will influence the rate of spread and the dilution of these combustion products. Although some of the features involved in these processes are well understood and can be handled analytically, many others cannot. In particular, those processes involving turbulent mixing between hot and cold gases when buoyancy forces are comparable to inertial forces are not well understood.

To illustrate the problems under investigation in this program, consider the sketch shown below of a fire in a room and the flow of products down an adjacent hall which is terminated by a vertical shaft. Turbulent entrainment of cold gas in a buoyant plume above the fire fixes the temperature and product concentration in the room ceiling layer. When this layer



spills over into the hall, the turbulent entrainment rate at the doorway can be as large as the flow of hot gas through the door. The velocity of the ceiling layer and the air flow to the fire area also will be affected by this entrainment rate. Finally, the flow of hot products up the vertical shaft will be dominated by turbulent mixing processes.

The problems discussed in this paper concern the experimental investigation of the turbulent transport of hot gas up vertical shafts (e.g. ventilation shafts, stairwells, or elevator shafts) or through horizontal passages such as halls, when natural convection alone is the important driving mechanism.

We have primarily considered the transient flow situations shown in the sketch. In both examples, the fluid in the tube is initially at density ρ_i, selected to model room temperature air. At the start of the experiment, the lower end of the "shaft" or one end of the "hall" is abruptly opened to allow mixing between the room temperature gas and a hotter ambient fluid of density ρ_a, such that $\rho_a < \rho_i$. In the vertical case, mixing between high and low density fluids occurs initially because of a Taylor instability at the interface, since high density fluid lies above the low density fluid. This instability rapidly grows into a large-scale turbulent mixing process which propagates up the tube to the top. Vigorous mixing continues for a long period throughout the tube. This process gradually transports the high density fluid out the bottom of the tube and replaces it with lower density material.

The replacement process in the horizontal tube is much simpler. In this case, a wave of low density material propagates along the top of the tube at a constant speed, and no turbulent mixing is observed. This wave front is reflected from the end of the tube, and the tube is almost completely drained of high density material in a single cycle. Buoyancy effects apparently damp out any interface instability. Tubes held at an appreciable angle with respect to the horizontal (30° or larger) exhibit features of both the horizontal and vertical cases.

Summary of Experimental Approach

The experimental program we have been following includes these features: (1) We examined the mixing phenomena associated with the flows described above in small scale models; salt-water mixtures are used to model the dense (cool) gas, and water alone to model the less dense (hotter) gas. In this program we have attempted to:

(a) Develop general scaling laws for the variation of density with time in the flow set up in a shaft which is a right-circular cylinder placed in an unlimited surrounding atmosphere. The diameter and length of the cylinder, and the initial density difference between inside and outside the vertical or horizontal shafts were the primary parameters.

(b) Develop an analytic model which can account for the observed mixing rates in these simple configurations.

(c) Carry out measurements with this technique to investigate the effects of geometric variations on the mixing rates. Limited external atmospheres and changes in the internal geometry of the shafts were investigated.

(2) We are examining the mixing phenomena when gases of different densities are used to model the hot and cold gases. Measurements are being made with realistically large density differences ($\Delta\rho/\rho > 1.0$) but uniform temperatures.
(3) The effects of heat transfer on the mixing phenomena and the magnitude of the heat transfer are being studied. In this work, temperature differences alone (rather than species changes) are used to produce the buoyancy forces in gases.
(4) Finally, the model is being extended to include heat transfer, large density differences, and geometric complexities.

Horizontal Case. Some results obtained for the horizontal case are shown in Figure 1, where the position of the wave front Z is plotted as a function of the time. Values of Z are normalized by the tube diameter d and the time by a time scale made up of the initial density difference $\Delta\rho_i = (\rho_i - \rho_a)$ (ρ_a is the ambient density and ρ_i the initial density inside the tube), the tube diameter d, and the gravitational constant g. The data show that the wave of low-density material propagates at a constant velocity whose magnitude agrees with the equation given in Figure 1. This result is in good agreement with a wide range of previous observations.

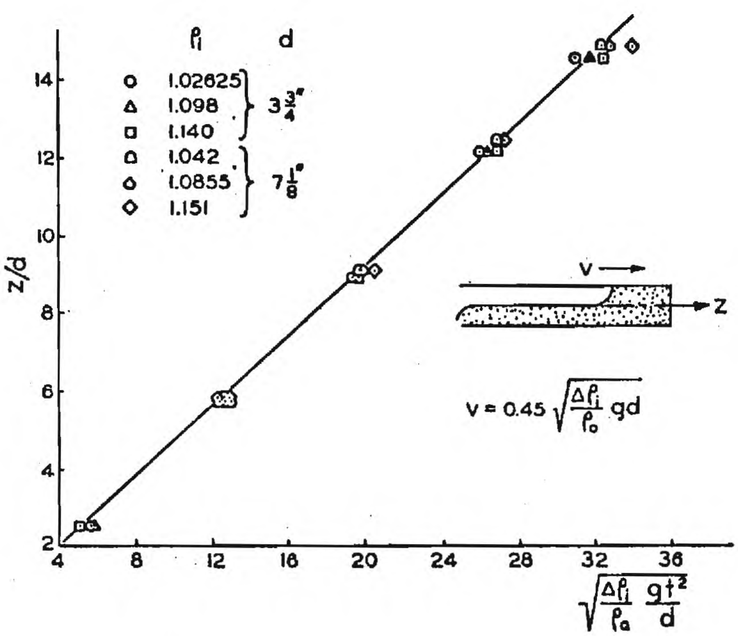


Figure 1.

Flow in Horizontal Tube.

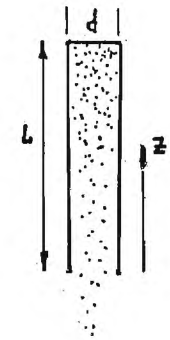
Vertical Case. In the vertical case, turbulent mixing plays a dominant role, and we have attempted to develop an ad hoc description of this process which will account for the dependence of the mixing rate on tube scales (length L and diameter d) and local density gradient ($\partial\rho/\partial Z$). We assume that the local diffusive flux (see Figure 2) is given by the product of the local coefficient of turbulent diffusivity D and the density gradient. The diffusivity is taken to be a product of a velocity fluctuation w' and a scale length s'. The scaling procedure is suggested in Figure 4, paragraph 1. The function $f \propto (L/d)^{1/4}$ is included to account for the experimentally observed dependence on L/d.

1. Turbulent Diffusion

(diffusive flux) $\equiv D \frac{\partial \rho_s}{\partial z}$ Assume: $D \propto w' \ell'$

Pick: $(w')^2 \propto \left(\frac{\Delta \rho}{\rho}\right) g \ell' \propto \left(\frac{1}{\rho}\frac{\partial \rho}{\partial z}\ell'\right) g \ell'$ and $\ell' \equiv d$

Then: $\boxed{D = K\, f\{L/d\} \sqrt{\frac{1}{\rho}\frac{\partial \rho}{\partial z} g d^4}}$ $f \sim (L/d)^{1/4}$



2. Continuity Eqn.

$$\frac{\partial \rho_s}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \rho_s}{\partial z}\right)$$ when $(\rho_i - \rho_a) \equiv \Delta\rho_i << \rho_a$

Let: $\theta \equiv (\rho - \rho_a)/(\rho_i - \rho_a)$; $x \equiv (z/L)$; and $\tau \equiv t \sqrt{\frac{\Delta\rho_i}{\rho_a}\frac{g}{d}} \left(\frac{d}{L}\right)^{9/4}$

Then: $\boxed{\frac{\partial \theta}{\partial \tau} = K \frac{\partial}{\partial x}\left(\frac{\partial \theta}{\partial x}\right)^{3/2}}$

Figure 2. Development of Continuity Equation.

When density differences are small, the continuity equation can be expressed in the form given in paragraph 2 of Figure 2, and the various dimensionless parameters used in presenting the experimental results are defined there. Boundary conditions and solutions for two geometric conditions are given in Figure 3. In paragraph 1, Figure 3, the simple vertical shaft case is treated. The separation of variables technique is applicable, and solutions are found to depend on the single unknown parameter K which appears in the expression for the turbulent diffusivity. (The separation constant α can be expressed as a function of K.)

The experimental results obtained in the salt water - water tests conform very well to the predicted results. Figure 4 shows the data first as a plot of the dimensionless density ratio $\theta = \Delta\rho/\Delta\rho_i$ evaluated at the top of the tube versus the dimensionless time τ, defined in paragraph 2 of Figure 2. In Figure 5, $\sqrt{1/\theta\{x=1\}}$ is plotted versus τ to illustrate the linear dependence of this parameter, which is predicted by the analysis (paragraph 1 of Figure 3). Experimental results for a large range of parameters ($1\ 1/2 \le d \le 7\ 1/8''$; $7.5 \le L/d \le 20.6$; $0.021 \le (\Delta\rho_i/\rho_a) = 0.15$) are successfully correlated with a single value of 0.53 for K, the constant in the diffusion coefficient.

The spatial dependence of θ on x is given by $F\{x\}$ term (see Figure 3); the agreement between measured and observed values is shown in Figure 6. Here, $\sqrt{F/\theta}$ is plotted against τ. Since $F\{x\}/\theta\{x, \tau\} = H\{\tau\}$, we should get a curve independent of x when data for various values of x are plotted in this manner. Figure 6 shows that this is correct as long as $\tau > 0.4$. When

1. Vertical Shaft

(a) at $\chi=1$: $\left.\frac{\partial\theta}{\partial\chi}\right| = 0$ and $\theta\{\tau=\tau_0\} = 1.0$

(b) at $\chi=0$: $\theta\{\tau\} = 0$

Solution: $\theta = F\{\chi\}\cdot H\{\tau\}$

$$\left(1/H\{\tau\}\right)^{1/2} = \left[1 + \frac{\alpha}{2}(\tau-\tau_0)\right] \text{ and } \chi = \left(\frac{6K}{5\alpha}\right)^{2/5}\int_0^F \frac{df}{(1-f^2)^{2/5}}$$

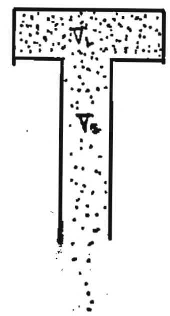
Data show: $\alpha_1 = 1.45$ and $K = 0.53$

2. Well-mixed Volume on Top

(a) at $\chi=1$: $\frac{V_r}{V_s}\left(\frac{\partial\theta}{\partial\tau}\right) = -K\left(\frac{\partial\theta}{\partial\chi}\right)^{3/2}$ and $\theta\{\tau=\tau_0\} = 1.0$

(b) at $\chi=0$: $\theta\{\tau\} = 0$

Similar solution → $\alpha_2 = 0.40$ when $(V_r/V_s) = 1.0$



3. Well-mixed Volume on Bottom.

Figure 3. Solutions for Vertical Cases.

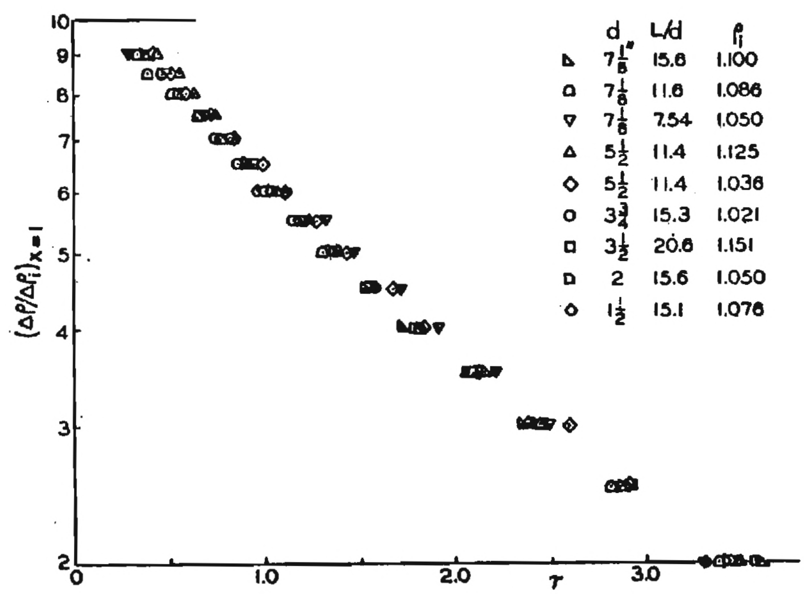


Figure 4. Decrease in Density at Top of Tube as a Function of Time.

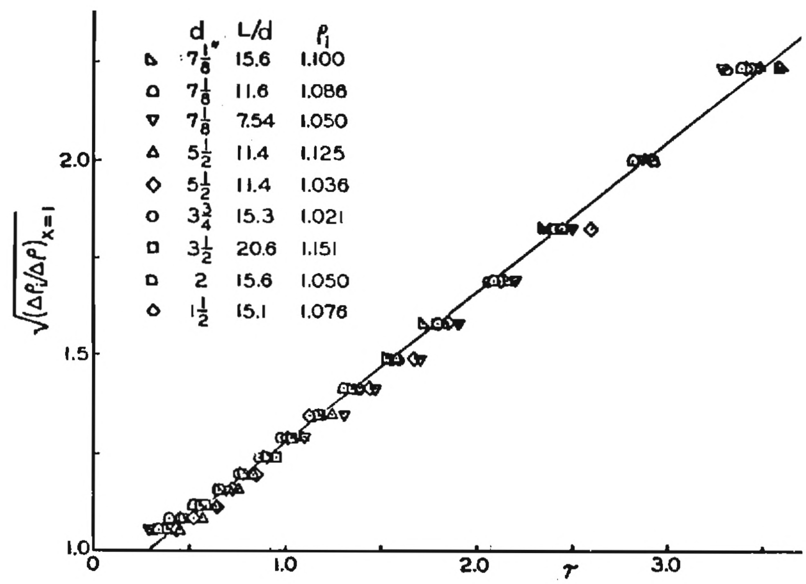


Figure 5. Variation of Density at Top of Tube with Time.

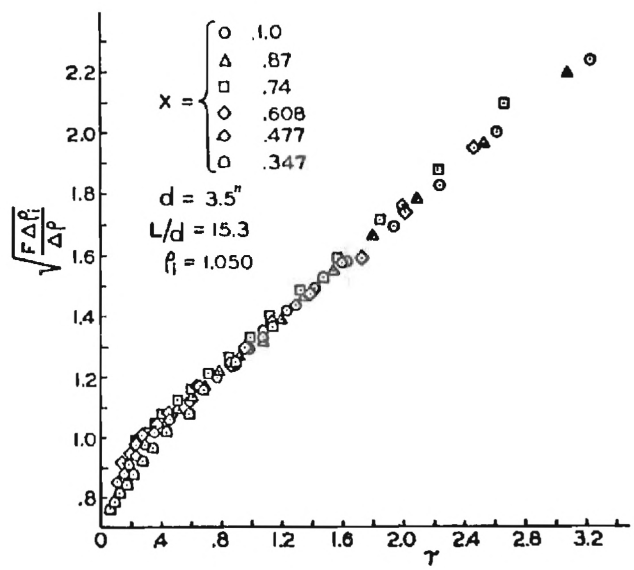


Figure 6. Spatial Dependence of Density Variation.

$0 \leq \tau \leq 0.4$, the wave is still propagating up the duct, and consequently the solution does not apply.

The good correlation of data given in Figures 4, 5, and 6 suggests that the approach taken here can be used in more complex problems. As an example, consider the duct shown in Figure 7, which represents a vertical shaft connected to a horizontal hall. The work with flow in horizontal passages alone showed that mixing or replacement rate for this configuration is relatively very rapid compared to that in a vertical shaft. Hence, this configuration can be analyzed by treating the hall as a region of uniform density connected to the outside world through the vertical shaft. This problem is also easily treated analytically (see Figure 3, paragraph 2), and now that the constant K has been determined, the θ versus τ slope can be calculated with no adjustable constants. The data presented in Figure 7 show first that the horizontal hall is well stirred (see agreement between open and closed points), and second, that the calculation (based on K = 0.53 found in the previous experiments) agrees well with these data.

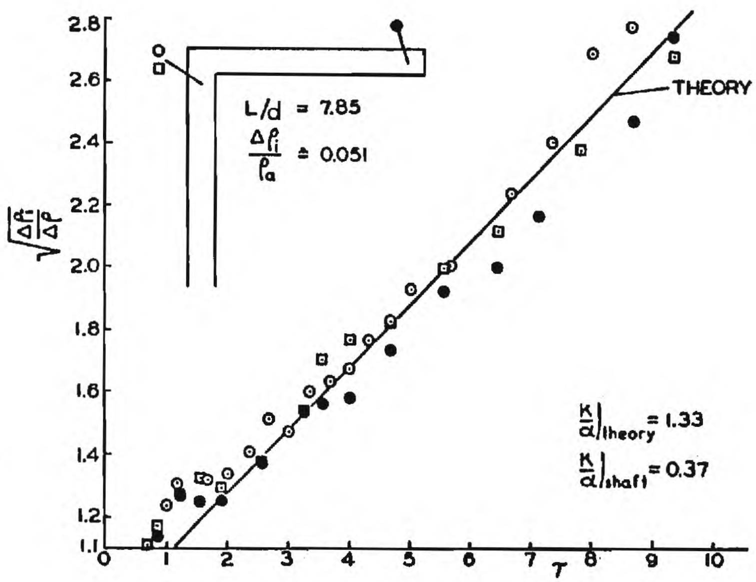


Figure 7. Shaft and Well-Mixed Hall Configuration.

In conclusion, the tests under item (1) above have been completed successfully, and a simple analytic tool has been developed.

Progress Report on Items (2), (3), and (4)

At present, items (2), (3), and (4) are being investigated. Apparatus for (2) has been completed, and preliminary experiments have been carried out for the vertical shaft geometry. Argon and sulfur hexafluoride (molecular weights 40 and 146) have been used to model the more dense gas, and air to model the lower density atmosphere. A tube 0.2 m in diameter by about 2.4 m long has been used for the shaft. Good qualitative agreement is found between predicted and measured variation of density with time, but the results of these tests and those described under item (1) differ by about a factor of two. This effort is being pursued.

Work on item (3) has also reached the point of producing initial results. The aim here is to develop an extension of the model, items (1b) and (4), to include estimates of the heat transfer to the walls set up by the violent turbulent motion within the shaft, and the influence of heat transfer on the mixing process. Hence, we are interested in model development rather than in precise modeling. Consequently, we have picked experiments which are reasonably simple to carry out and compare with mathematical models.

Analysis of our results indicates that we can assume that turbulent diffusivities for mass and energy are proportional, and that the form for the mass transport diffusivity obtained from item (1) is appropriate for the problem considered here.

Some results of tests and calculations are shown in Figure 8 and 9. The first example, Figure 8, involves an unsulated tube cooled at the top and open at the bottom. The calculated results are fitted by matching the experimental temperature at $x = 1.0$. In Figure 9 are shown calculations of gas temperature distribution set up in a tube with constant bemperature walls. A heat transfer parameter h is varied here. The experimental values agree with calculations for h of the order of 10^{-3} to 10^{-4}.

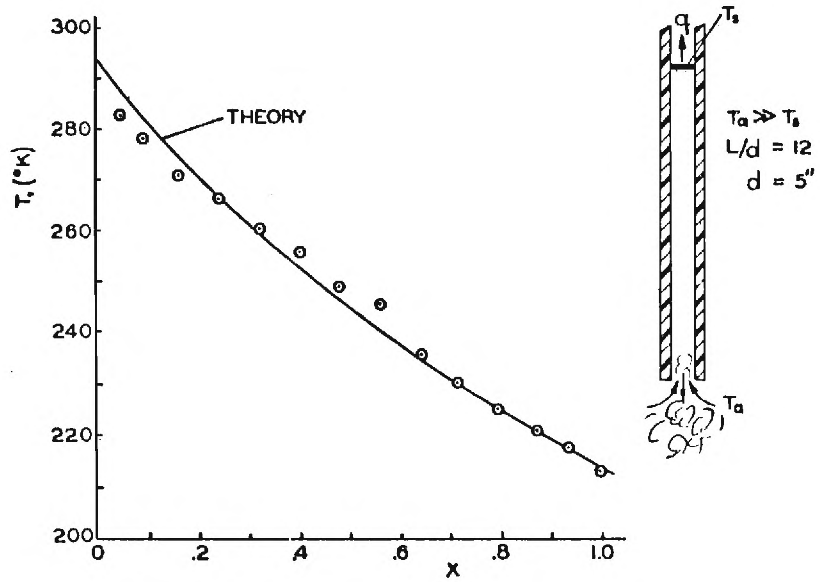
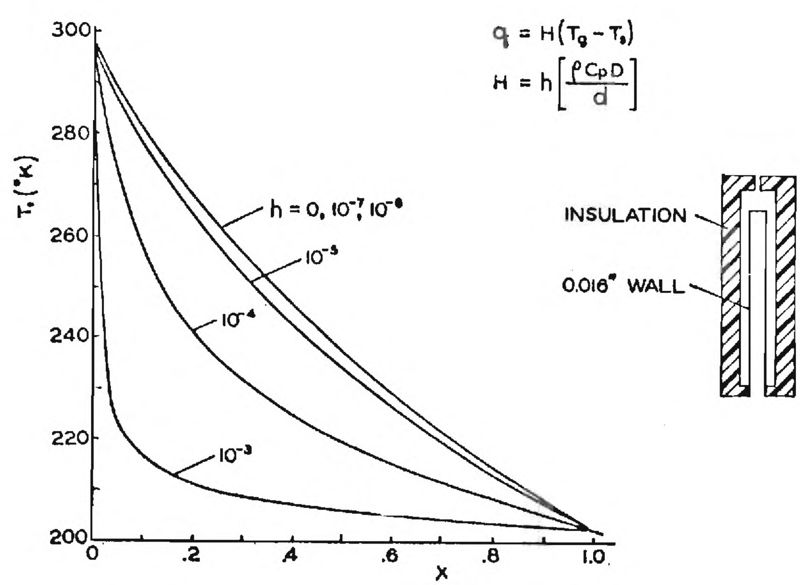


Figure 8. Gas Temperature Variation in Tube Cooled at Top.

Figure 9. Gas Temperature Variation in Tube with Constant Wall Temperature.



In summary, item (1) above was arranged to clarify the dependence of the mixing phenomena on various scales under conditions that were simplified because we used small density differences and did not have the complications introduced by heat transfer. Item (2) extends the investigation to cover mixing of gases and large density differences. Finally, in item (3), all effects including heat transfer are present at once. When we understand the complete set of phenomena, we will be able to predict mixing rates in fire-like situations [item (4)]. This result will be an important part of any overall computer model of a building fire.

UNIVERSITY OF NOTRE DAME

NSF GRANT NO. GI-37191

FIRE AND SMOKE SPREAD IN CORRIDORS

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PROJECT SUMMARY

The research project described here, which is under NSF Grant GI-37191, is directed toward a better understanding of fire and smoke spread. This is to be accomplished through the development of experimentally based numerical analytical models which can be used for predictive as well as guidance purposes. The proposed research program is highly coupled to the fire programs at the National Bureau of Standards. Data gathered at NBS and the University of Notre Dame will be used for an assessment of the validity of the analytical approach. The analyses will be applied to small-scale and full-scale fire spread problems such as the tunnel test, model corridors, and the full-scale corridor to mention a few applications. With the availability of such analyses, the relationship in terms of scaling between full-scale and small-scale tests can be examined. The analysis can be used for guidance on the usefullness of hazard tests as well as explaining the behavior of full-scale tests.

The analytical approach employed in this investigation is separated into two phases. The initial phase involved solving the basic conservation equations for the two-dimensional preheat problem in a corridor wherein the equations are those for a two-dimensional, parabolic, turbulent channel flow including the effects of buoyancy, compressibility and radiation. The second phase involves the solution of the full elliptic equations enabling the description of the backflows and recirculation regions. These analyses are highly coupled to experimental studies conducted on both a full-scale and a small-scale. The full-scale experiments are those conducted in the National Bureau of Standards corridor facility. This data provides basic full-scale comparison to judge the overall validity of the analytical results. The small-scale experiments, which are necessary due to the fact that it is not possible to instrument a full-scale facility in sufficient detail, provide necessary information on analytical turbulence, combustion, and radiation models. These small-scale experiments also provide an additional assessment of the validity of the analytical programs. One of the major accomplishments will be to determine the role of radiative heat transfer due to soot, absorbing-emitting gases and wall radiation in spread problems.

PROGRESS REPORT

Despite the many groups involved and dedicated to the reduction of unwanted fire hazards, the prediction, with a reasonable assurance, of the behavior and spread of unwanted fire and smoke is still in the developmental stage. It is strongly felt by this group that it is necessary to have an integrated program ranging from very basic studies of various transport mechanisms, both experimental and analytical in nature, to studies of the overall behavior of fire and smoke spread, again both experimental and analytical in nature. Only when this type of program has been performed will the work of the researcher have its full impact on the fire problem. It is this approach that the present investigation is following.

The initial phases of this investigation were directed toward the development of an analytical model which contained sufficient detail to describe some of the physical events which occur in corridor preheat periods. Experimental observations for this phase of the work are supplied primarily through the NBS corridor program. Once this problem was satisfactorily completed a more detailed analysis was initiated. This second-phase analytical description of the fire and smoke spread problem goes into considerably greater detail relative to the behavior and the effect of the various transport phenomena involved in this problem. Primary experimental data input for this phase comes not only from the NBS corridor data, but also from small scale experimentation in the Combustion Laboratory at the University of Notre Dame.

Details of each phase will be presented in the following sections. Further details on the various phases of the investigation can be found in the technical reports referenced later in this presentation.

Analysis

The initial analysis employs the numerical physical-variable approach on a two-dimensional unsteady turbulent flow in a channel shown schematically in Figure 1. The flow was considered to be parabolic in nature (i.e., boundary layer type flow). This is in distinction to treating the full elliptic problem which could account for recirculation regions in high buoyancy flows. This channel configuration is considered at the present time to be an approximation to the full-scale NBS corridor as well as the E-84 tunnel geometry.

This initial analysis uses physical variables in numerically solving the basic set of conservation equations. This approach is employed instead of the stream function and vorticity approach. In this physical-variable formulation, the conservation equations, are written in terms of velocity, temperature, and pressure. It is strongly felt by this research group that the physical-variable formulation is the only realistic approach to a combustion problem of this type which contains severe temperature gradients, high buoyancy, compressibility, and ventilation effects. This, however, is an added complication since stable solutions are generally difficult to obtain with the use of physical variables. The results using the analysis generated for the preheat period of the spread problem indicate that this difficulty has been overcome.

The initial preheat analysis, as stated previously, is based on a set of two-dimensional parabolic (in the sense that downstream conditions cannot propagate upstream) unsteady equations. The equations are written for a compressible fluid with buoyancy, turbulence and radiative transfer included. The limitation to parabolic equations requires that this particular channel problem contain a significant through-flow. The turbulent transport laws and the radiative term appearing in the analysis must also be modeled. Here, the thermal conductivity and viscosity are taken to be the effective values of the turbulent thermal conductivity and viscosity and are specified to be constant at a value 200 times normal laminar values. Until the analysis reaches a higher level of sophistication, the simple constant-value model will be employed. To account for radiation, a one-dimensional radiative transport model is employed. It is felt that since there is no recirculation in the present analysis (where significant temperature gradients would exist in the axial direction) a one-dimensional approximation should give reasonable predictions. The method of approach is a zonal technique (see reference (2)* for details of the derivation of the radiation terms).

Figure 1 is a schematic of the corridor divided up into cells with centers noted by I, J. The basic equations are then put into finite difference form based on the cell model as discussed in reference (4). To solve the above mentioned set of equations, it is necessary to specify the initial velocity and temperature distributions within the channel and to specify the inlet temperature and velocity profiles as well as conditions along the walls of the channel. The inlet conditions, which are functions of time, are determined from actual NBS corridor data.† The inlet velocity and temperature profiles as employed in the present analysis are given in Figures 2 and 3. It should be noted that these profiles are obtained by using the pitot tube data† and the thermocouple data from the burn-room doorway in the corridor facility prorated to the width of the corridor. Based on these data the general profile for the velocity is taken to be a slug profile while the temperature profile was taken to be triangular. The walls of the channel are considered to be adiabatic (no heat loss to the surroundings); the usual no-slip condition ($u = v = 0$) also applies at the walls.

In this presentation a complete set of results can now be set forth and discussed. One particular case will be presented and discussed in some depth to give an idea of the type of results which can be generated by the analysis. The case considered is as follows. The inlet and initial conditions discussed previously are employed and the resulting temperature profiles at a distance 2.5 times the channel height downstream of the entrance are examined. The analysis includes the effect of radiation from walls and soot where the soot layer thickness is 1/3 the channel height; the soot volume concentration is varied. Without radiation, the temperature profile for the adiabatic boundary condition is as noted in Figure 4. When radiation from the walls (in the absence of soot radiation) is considered, the ceiling temperature is reduced and the floor temperature is increased. As the soot concentration increases, the ceiling temperature increases and approaches the no radiation case. The soot layer becomes optically opaque and the effect of wall radiative transfer decreases. At the floor, one must consider the effect of both the wall and soot radiation; thus, its behavior is more complicated. This can be seen by noting that the soot concentration, $f_v = 10^{-6}$, has the largest wall temperature. At the lower soot concentration the lower ceiling temperature is reflected in the lower floor temperature. At higher soot concentrations, the effect of the ceiling is reduced by the increased soot opacity.

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*Reference numbers refer to items in the Reports and Publication Section.

†Since the use of the parabolic equations requires a significant through-flow, it was necessary to add a fairly high base flow (t=0) to the conditions found from pitot tube data.

With this program, the global behavior of the preheat period in a corridor with significant through-flow has been examined. The effect of various soot layer depths and various soot concentrations have been examined, and the effects of various assumptions such as one-dimensional radiative transfer, etc. have been justified (6). It is now important to move on to the more significant case where buoyancy effects become strong relative to the through-flow. In other words, one must consider the full elliptical equations to provide for the possibility of recirculation and ventilation. This phase of the analysis has been initiated. At the time of the writing of this presentation, the program is being run for various test cases to establish that it is working properly. The development of this analysis, including radiative effects, constitutes the major thrust of the group in the analysis area. The future directions of this program are discussed in the appropriate section of this report.

Experiments

The experimental program is directed to a full-scale study as well as to a small-scale study. As previously indicated, the full-scale study employs the existing and future NBS corridor facility. The previous NBS data have been examined in some detail and have been used to provide physical direction for the previously discussed initial analysis. Future full-scale burns by the NBS group and with active participation by the Notre Dame group are planned.*

The small-scale tests, which are being carried out at Notre Dame, are directed toward obtaining detailed local data in a combustion situation similar to the corridor problem discussed in the analysis section. In general, a full-scale facility cannot be instrumented to the point of obtaining large amounts of local data. With the local data, which can be provided by the small-scale experimental apparatus, analytical models such as those for combustion and radiative transfer can be not only judged for their utility in the small-scale situation but also for use in the full-scale problem. It should be clearly pointed out that the small-scale facility does not attempt to model the full-scale corridor, but it does provide the means for checking the analytical approach.

The small-scale facility is basically a small wind tunnel capable of operating at very low through-flow rates (currently, an average tunnel through-flow velocity of 2 ft/sec). Figure 5 presents a schematic diagram of the tunnel. For details of the construction of the apparatus, the interested reader is referred to reference (3).

The design and construction of the small-scale facility has been completed. Initial calibration tests without injection through the porous injection plate show that the tunnel produces a flow field which is uniform in velocity across almost the entire inlet plane (see Figure 6); the only

*It should be noted that due to complications with the corridor facility, progress in this area has been delayed slightly.

deviations from uniformity occur in the very thin boundary layer. Downstream, the boundary layer thickness, as seen in Figure 7, increases and the core velocity increases slightly. At this stage of the calibration tests injection of air through the injection box was initiated. Results of these studies, wherein the free stream velocities and the injection blowing rates were varied, indicate that the injection system is operating properly. The test facility is ready for injection of a hydrogen-nitrogen gas mixture which will provide for a clean combustion process (i.e., negligible soot formation). Temperature, velocity and concentration profiles will be obtained from the facility for appropriate input to the analysis. Future experiments will be discussed in the appropriate section of this presentation.

ACCOMPLISHMENTS

Considerable progress has been made in the development of both the analytical and experimental phases of this research program. The most significant accomplishments of the research program to date are as listed below:

(1) The successful development of a two-dimensional, compressible, physical-variable analysis for the preheat period in corridors with significant throughflow.

(2) The introduction of nongray gas and soot radiation in the above mentioned analysis.

(3) The development of a time-wise efficient computer program for the solution of the conservation equations including radiative transfer.

(4) The development of an analytical program which includes the possibility of recirculation in strongly buoyant flow situations.

(5) Construction of a small-scale tunnel facility for assessing the validity of the analytical models.

POTENTIAL APPLICATIONS

It is not difficult to justify the need for an analytical approach to fire spread problems. Small-scale testing has proven to be rather ineffective in the past for predictions of the behavior of fire spread on the full-scale level. Full-scale testing is time-consuming as well as expensive; it is also difficult to instrument a full-scale test to the degree that is necessary for a full understanding of its behavior. With an analytical model to support experiments, a good portion of the present testing problems could be solved.

In recent years a great deal of concern has been raised about the flammability hazard of materials. An example of the difficulties encountered with hazard testing is the present confusion concerning the E-84 tunnel test primarily in regard to testing of plastic materials. A present concern is also the flammability hazard of floor coverings. Even with the introduction of the flammability standard for carpets, the behavior of floor covering in a full-scale fire is still in question. A number of full-scale tests involving floor coverings have been undertaken; these are primarily corridor experiments. An example of the difficulty with even the full-scale tests is the difference in behavior found in the IITRI facility and NBS corridor carpet tests.

The search for a proper testing method for floor covering (as well as other meaningful test methods) and the relationship of these tests to actual fire behavior and/or full-scale testing is of common concern at the present time. The previously mentioned E-84 tunnel test is one example. Other examples of small-scale testing are the E-162 radiant panel test, the UL992 Chamber test, the NBS radiant panel test. Even at the present time, there is no clear-cut way in which to quantitatively relate the behavior of the small-scale tests to actual fire behavior. In part, this is due to a lack of full understanding of scaling relationships as well as a lack of full understanding of the role of the various modes of energy transfer. One primary example of the latter is the lack of understanding of the role of radiation in fire spread behavior.

It is fully understood that the mechanisms involved in combustion situations such as that encountered in unwanted fires are extremely complicated and difficult to model. However, it is felt that the present state of the art is such that reasonable models can be generated. With the help of a large-scale computing effort, these models can be fed into a total analysis which will give a reasonable estimate of fire behavior. This is no easy task but with a proper research program it can be accomplished in a reasonable length of time. With the understanding that an analytical approach to the fire spread problem is feasible, the availability of such an analysis for describing fire behavior would be of tremendous advantage in sorting out some of the difficulties encountered in full-scale and small-scale testing. A highly coupled experimental-analytical program dealing with the behavior of the E-84 tunnel should give guidance as to the usefullness of E-84 for hazard testing. The effect of energy loading, mass flow, boundary contributed energy and dimensions of the tunnel can be sorted out with a minimum of effort. Once the reliability of the analysis has been established by a few experimental runs, the analysis can be used for parametric variation with a fair degree of confidence. With the availability of a reliable analysis, the effect of energy contributed by lining materials, the effect of ventilation, the effect of gas-phase combustibles and the influence of radiative transfer in the full-scale corridor can be examined with a minimum amount of difficulty. The relationship between small-scale tests such as the model corridor and the full-scale corridor can be established. The importance of radiant heating, such as applied to the proposed radiant panel hazard test, could be determined.

It is fully realized that the above statements will not be fulfilled overnight and will take a great amount of effort. On the other hand, it is strongly felt that these goals are within reach. The previous paragraphs in this section have been primarily directed toward the problem of hazard testing with specific reference to the NBS program. This is not to imply that the overall fire problem in the sense of fire spread in an actual building is unimportant.

FUTURE MILESTONES

The future milestones related to this project are many. The development of the full unsteady elliptical analysis is certainly the next major goal of this program. This program will then be refined through improvements in the species diffusion models, the combustion model, and the radiation model which can account for wall, gas and soot radiation. This is certainly an ambitious program, but with sufficient effort on the analytical program as well as significant input from the experimental program, it is within reach.

Significant future developments which will have to occur in the experimental program include carefully conducted small-scale combustion experiments where the various transport phenomena such as mass diffusion, momentum transport and radiative transport as well as the combustion processes are carefully considered. The small scale apparatus will be run with various gaseous fuels to provide information on the models discussed above. In addition, a smoke generation apparatus has been purchased and will be installed in the apparatus to provide information on the effect of smoke on transport phenomena.

It is obvious that future tests with the NBS large scale facility will have to be conducted. Input on instrumentation by the Notre Dame group will enable better use of data as input to the analytical models.

REPORTS AND PUBLICATIONS

1. J.L. Novotny, Progress Report to NSF on Grant GI-37191, Fire and Smoke Spread in Corridors, August 1973.

2. J.L. Novotny, "Formulation of One-Dimensional Radiative Flux for Non-Homogeneous Nongray Gases and Soot," University of Notre Dame Technical Report TR-37191-74-1, February 1974.

3. J.R. Lloyd, J.V. Golden and P.K. Schroeder, "Design, Construction and Evaluation of Small Scale Fire and Smoke Spread Facility," University of Notre Dame Technical Report TR-37191-74-2, February 1974.

4. M. Doria, "Fire and Smoke Spread in a Corridor: The Preheat Period Analysis, 2-D Parabolic Flows," University of Notre Dame Technical Report TR-37191-74-3, February 1974.

5. J.L. Novotny, Progress Report to NSF on Grant GI-37191, Fire and Smoke Spread in Corridors, February 1974.

6. J.L. Novotny, J.R. Lloyd, M.L. Doria, and T.C. Ku, "Fire and Smoke Spread in Corridors," Proceedings of the 1974 Polymer Conference Series, University of Utah, July 1974.

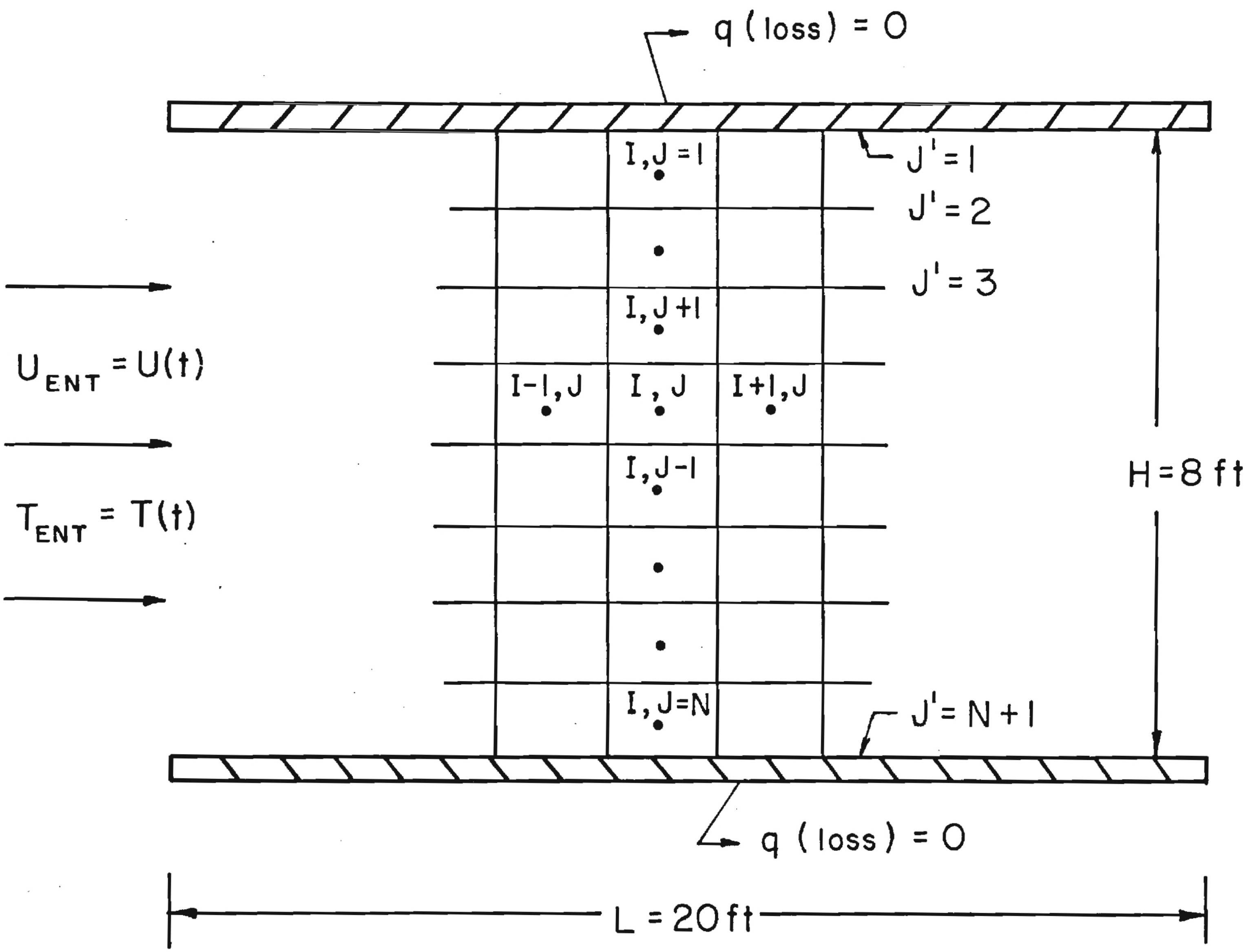

Figure 1. Channel geometry.

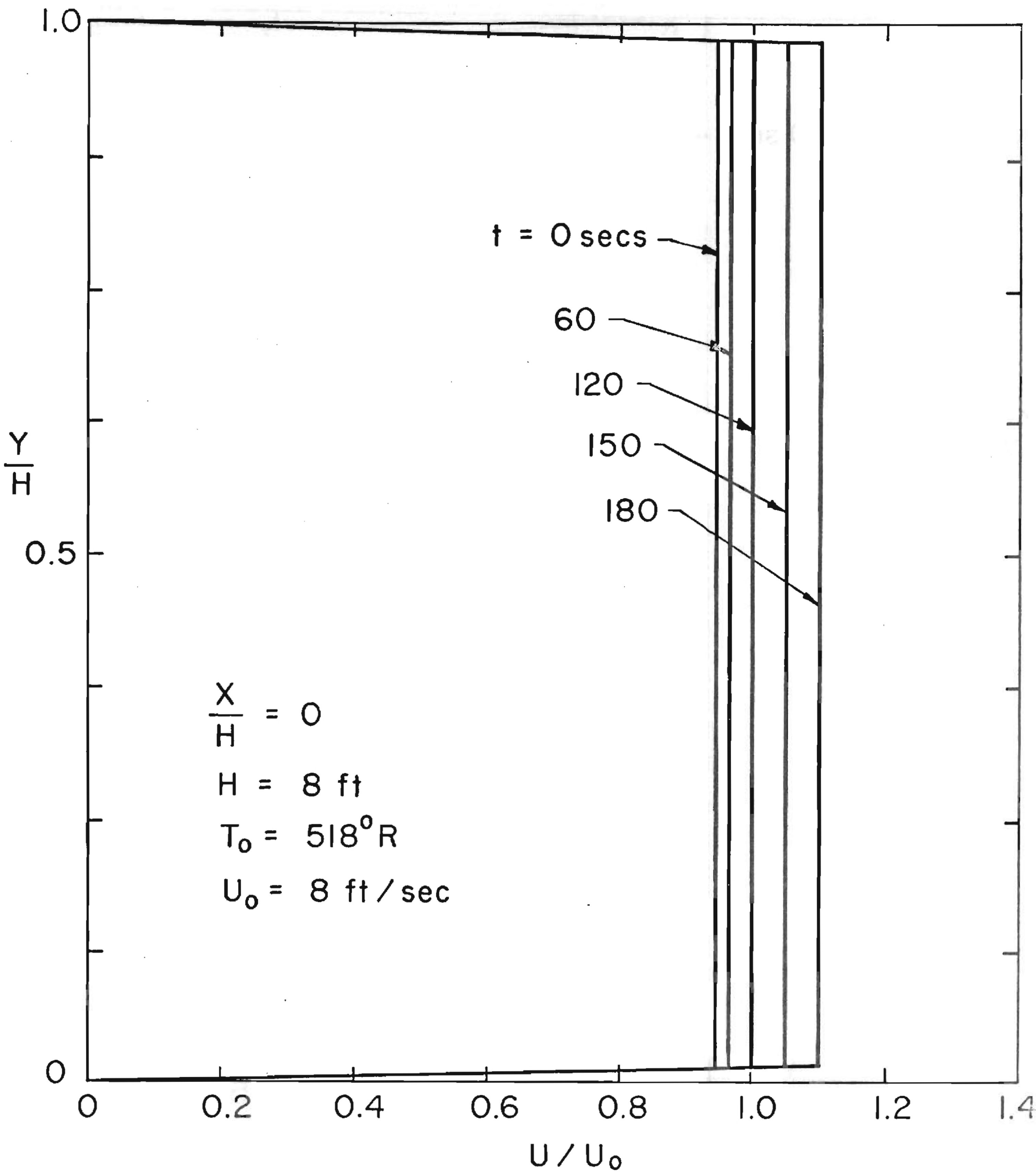

Figure 2. Inlet velocity conditions as a function of time.

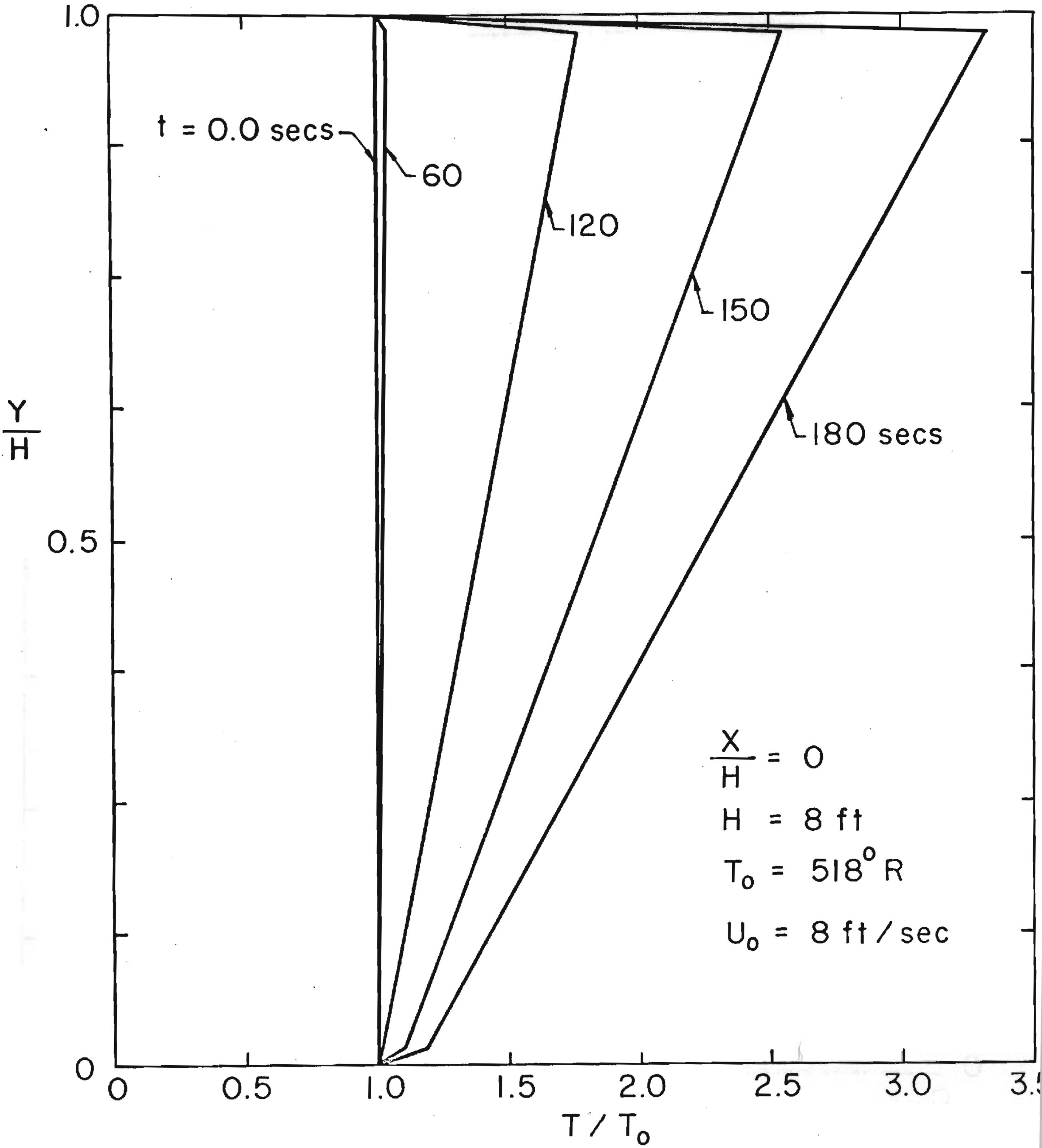

Figure 3. Inlet temperature conditions as a function of time.

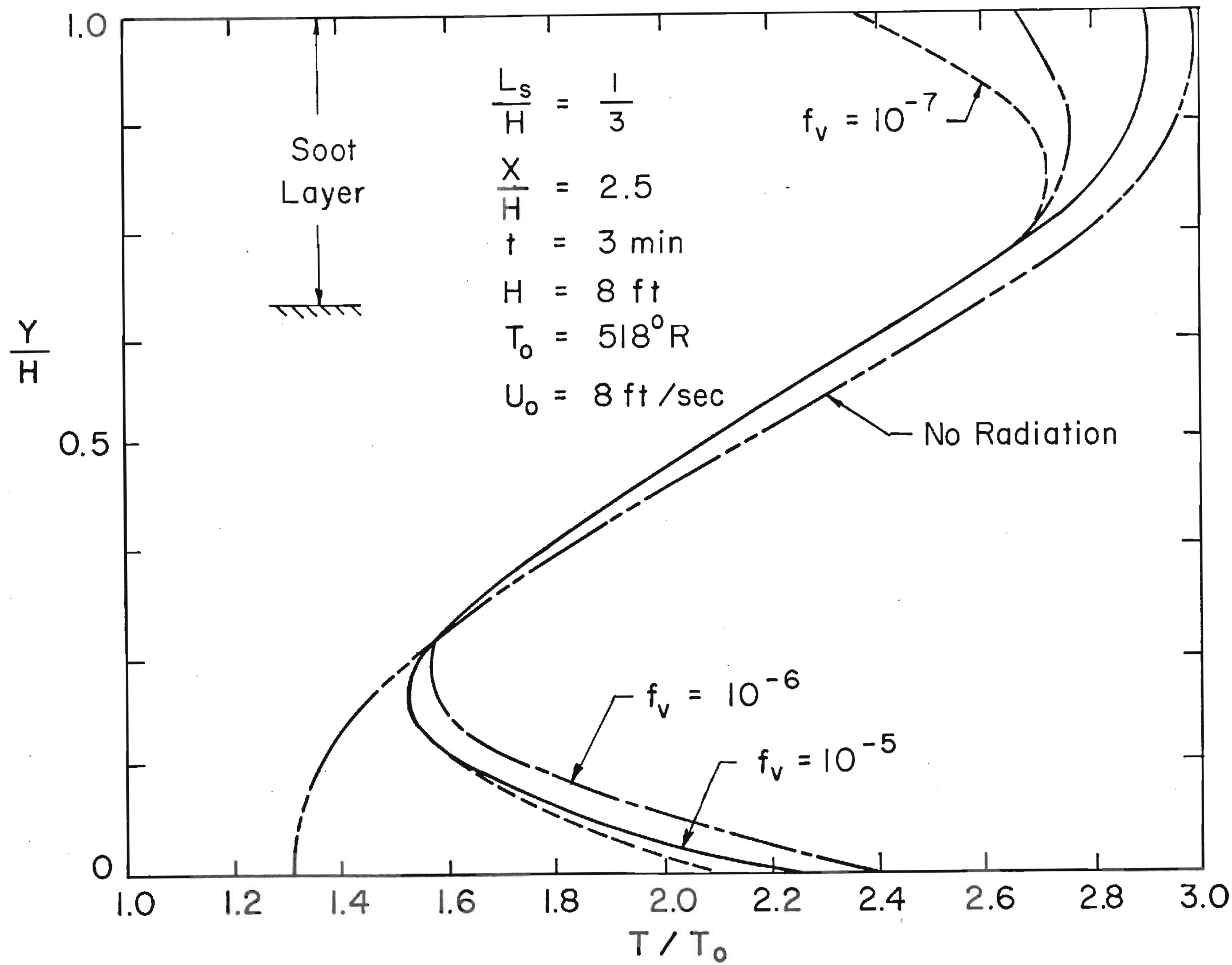

Figure 4. Temperature distributions for various soot concentrations.

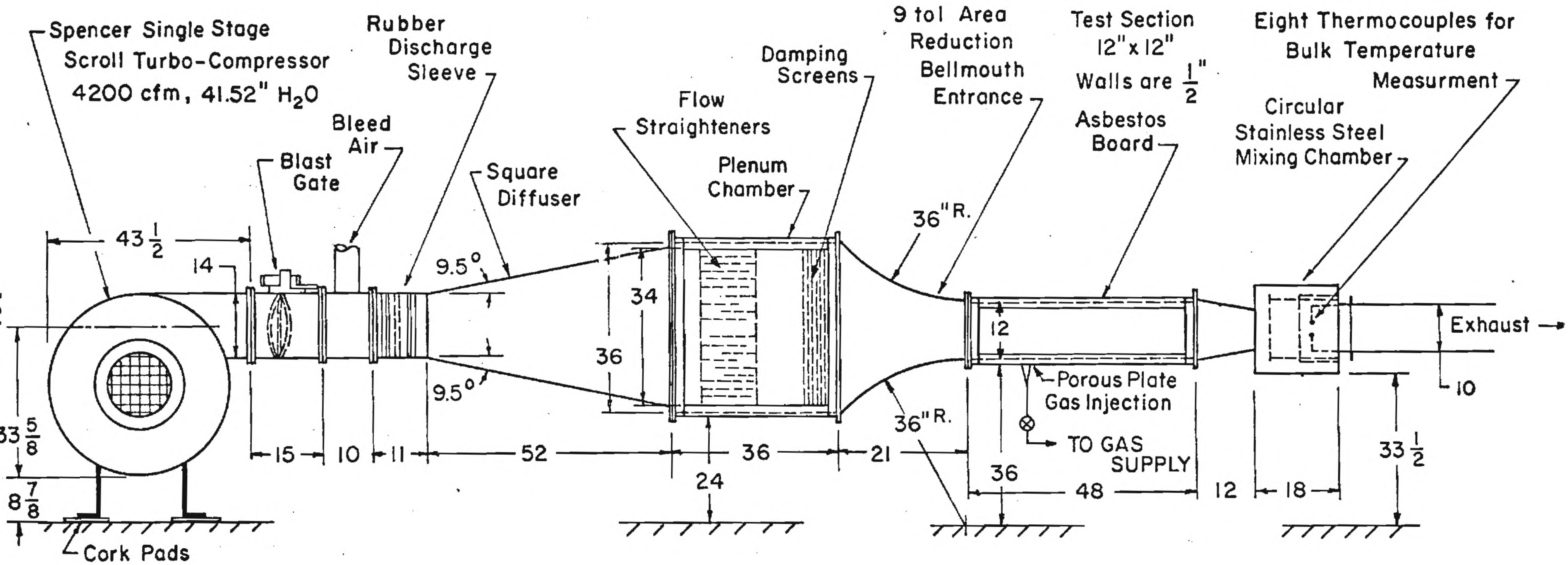

Figure 5. Schematic diagram of the small-scale experimental apparatus.

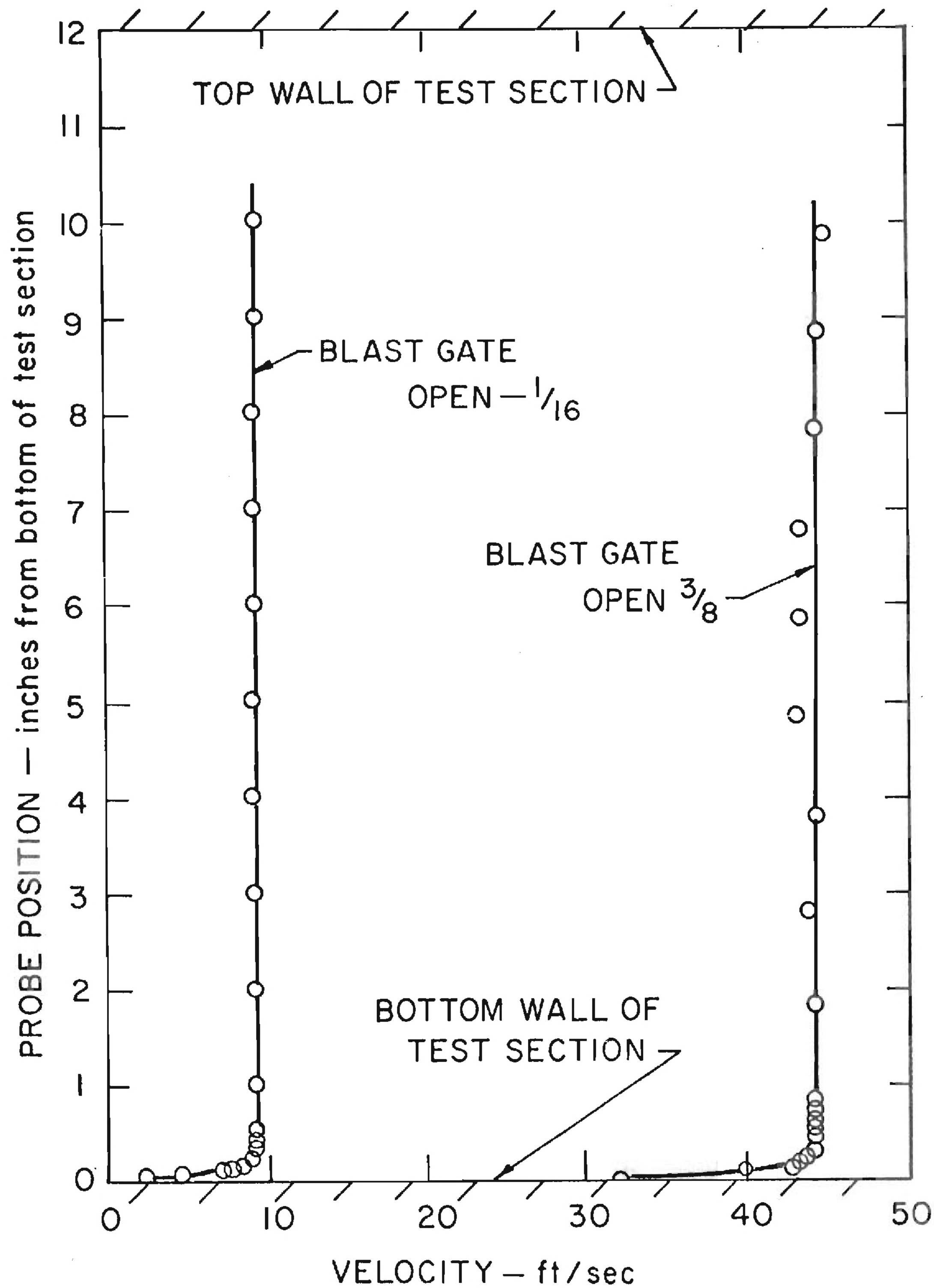

Figure 6. Inlet Plane Velocity Profiles

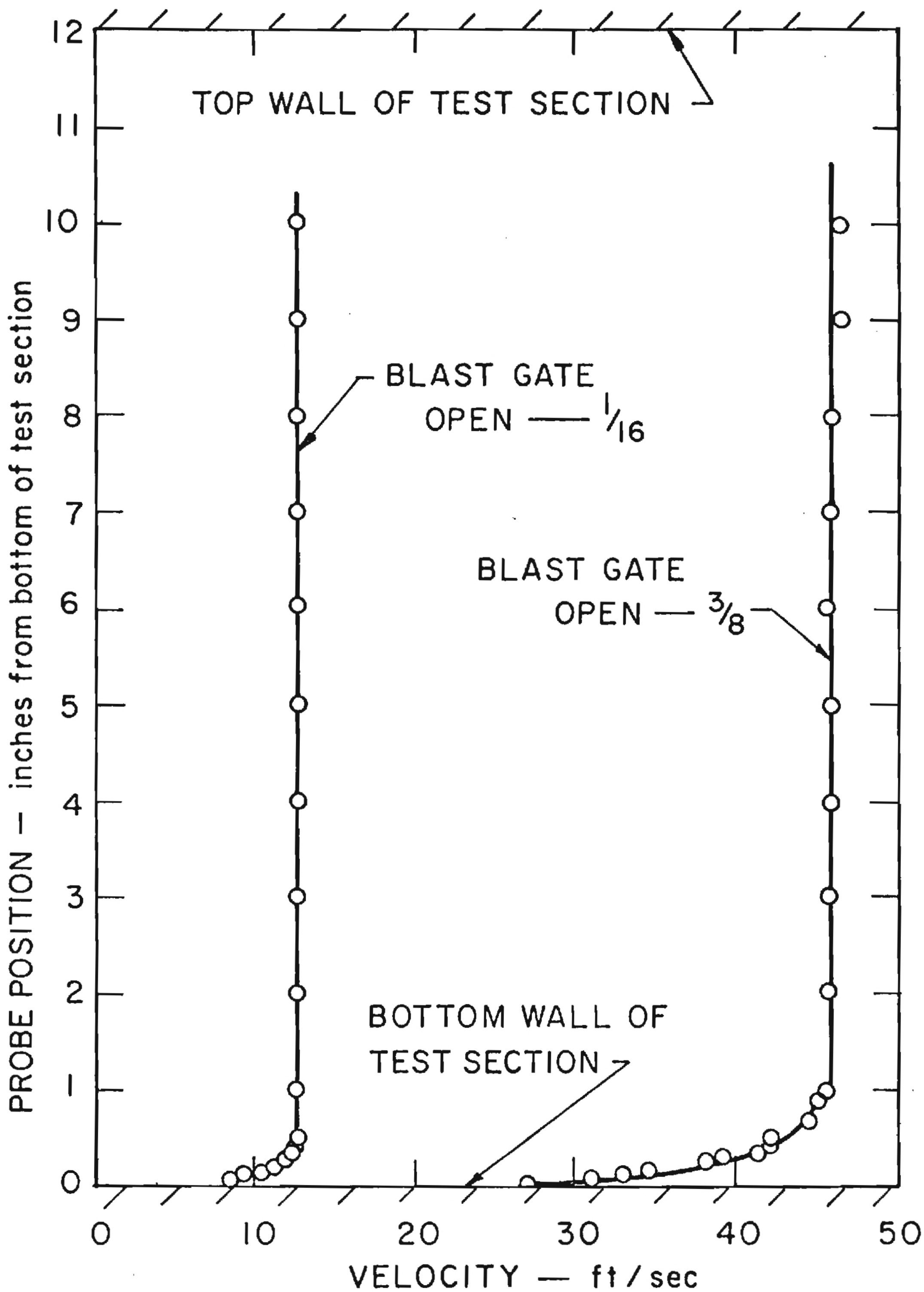

Figure 7. Velocity Profiles 25 3/8" from Inlet Plane of Test Section

PROJECT SUMMARY REPORT

prepared for

NSF/RANN Conference on Fire Research

Institution:	School of Aerospace Engineering Georgia Institute of Technology
NSF Grant No.:	GI-40782
Grant Title:	Properties of Combustion Products from Building Fires
Principal Investigator:	Dr. Ben T. Zinn, Professor School of Aerospace Engineering Georgia Institute of Technology Atlanta, Georgia 30332 (404) 894-3033
Other Professional Personnel:	Dr. Eugene A. Powell, Assistant Professor Robert A. Cassanova, Research Engineer C. Perry Bankston, Graduate Student
Consultants:	Dr. Leon H. Zalkow, Professor of Chemistry Dr. Clyde Orr, Jr., Regents' Professor of Chemical Engineering

PROJECT SUMMARY

Objectives

The first objective of this program is to develop the facilities and experimental techniques that are needed for detailed determination of the characteristics of smoke and gaseous products produced by the combustion of various building and furnishing materials. These techniques will allow the determination of particle size distribution, total mass of smoke particles, chemical properties of both smoke and gaseous products, and the optical properties of smoke. This objective also includes the determination of the relationship between various smoke properties and the currently measured light extinction coefficient.

The second objective of this program is to better define the conditions under which hazardous concentrations of smoke, lachrymators, and toxic gases develop in building fires. This involves determining the dependence of the smoke and gaseous products generated by the combustion of various materials on the size of the burning sample and the volume of the test chamber, the geometrical configuration of the burning sample, the temperature and composition of the chamber atmosphere, the type of burning (i.e., flaming or non-flaming combustion), and the amount of ventilation.

The third objective of this program is to develop a small-scale testing method that could be used to predict the characteristics of the smoke and gaseous products generated in full-scale fires. This involves an assessment of the relevance and shortcomings of existing smoke-chamber tests as well as determination of the physical factors that have the greatest effect on smoke and gaseous products generation.

Research Plan

To pursue the objectives outlined above the research project has been divided into two tasks that are concerned with different aspects of this program. Task I is concerned with the design, fabrication, installation, and calibration of the experimental facilities needed for performing the research. Furthermore, this task is concerned with the development of the measurement techniques needed for the detailed determination of the properties of smoke and gaseous products. Task II is concerned with the detailed determination of the characteristics of the products generated during combustion of various materials in a small-scale combustion chamber under carefully controlled conditions.

At this time the work being conducted under Task I is nearing completion. A summary of the progress made and some of the problems encountered is given in the next section.

PROGRESS REPORT

The following facilities are being developed under Task I for the determination of the nature of smoke: (1) Combustion Products Test Chamber, (2) Combustion Products Sampling and Chemical Analysis System, and (3) Optical Aerosol Analysis System.

Combustion Products Test Chamber. The Combustion Products Test Chamber (CPTC), shown in Figure 1, will be used for the combustion of various samples under carefully controlled conditions. The CPTC consists of an insulated solid outer shell and a perforated inner shell. This feature allows the ventilating gas mixture, flowing from the metering valves into the plenum between the shells, to slowly and uniformly flow into the combustion zone surrounding the tested sample. The flow of ventilating gas through the perforated shell prevents adsorption and deposition of condensable vapors and solid particles on the surface of the inner shell so that all combustion products flow into the Sampling Section. The flow of the ventilating gas allows control of the temperature and composition of the chamber atmosphere. Furthermore, this flow prevents the accumulation of combustion products in the chamber by continuously sweeping them out through the vent at the top of the chamber. Provisions are made for changing the temperature of the ventilating gases and porous shell. Varying the emissivity of the porous surface by use of suitable coatings or polishings permits evaluation of the effects of radiant energy.

In a typical test, a small sample of the material to be tested will be positioned within the inner shell. Non-flaming combustion will be maintained by either the convection of hot ventilating gases or the use of a radiant heat source, or both. A propane flame will be used to initiate

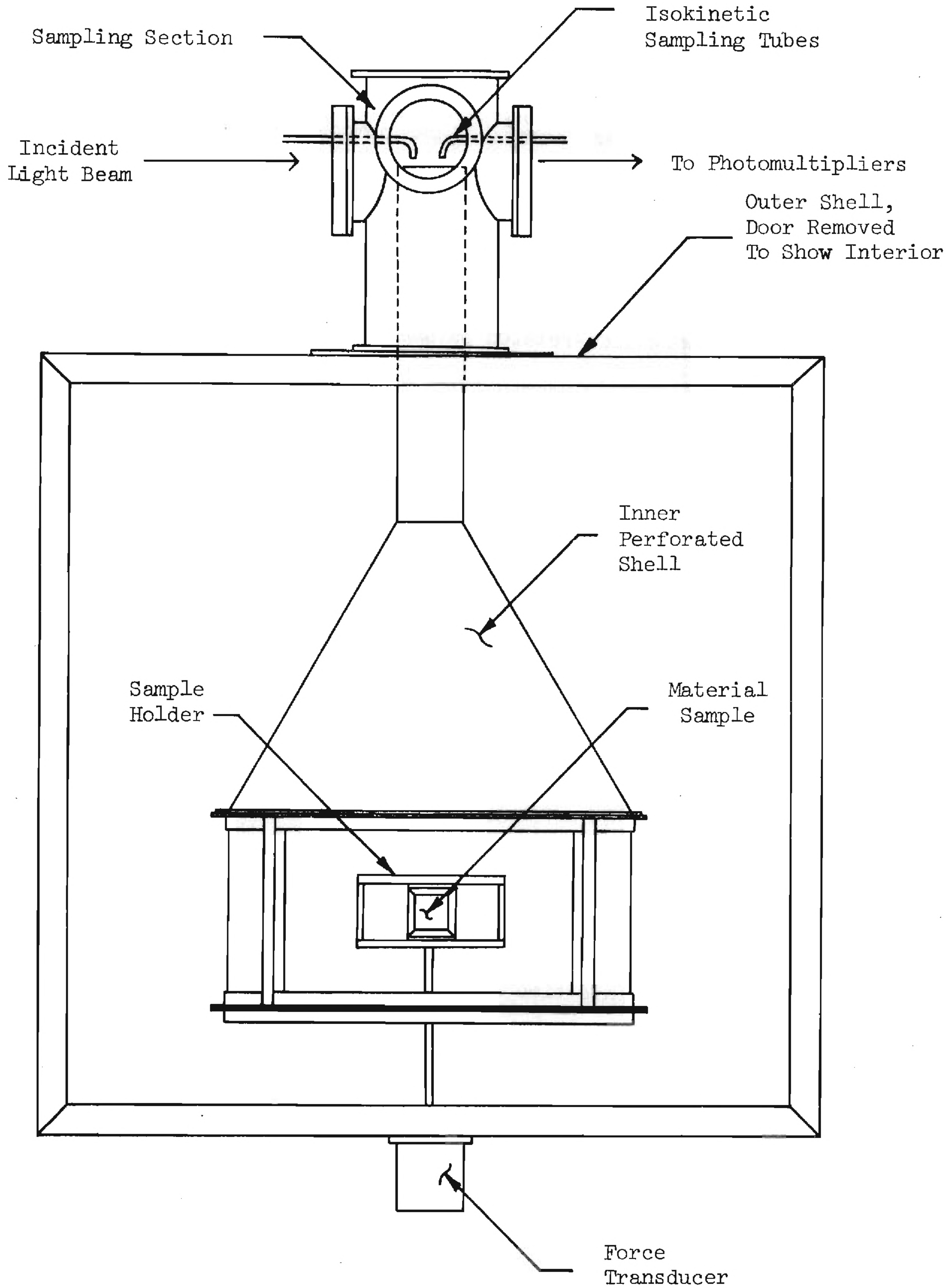

Figure 1. Combustion Products Test Chamber.

flaming combustion. During a test the mixture of the products of combustion and ventilating gas flow upward through the converging section into the Sampling Section where measurements of gas composition, smoke particle characteristics and temperature are made. A force transducer has also been included to monitor the weight loss of the sample during combustion.

The Combustion Products Test Chamber permits a systematic variation of the following combustion-related parameters: (1) temperature and flow rate of ventilating gas, (2) composition of the ventilating gas, (3) type of combustion (i.e., flaming or non-flaming), (4) size, shape, and composition of the sample, and (5) emissivity of the porous shell. For non-flaming combustion the radiant heat flux to the sample can be varied. Different ventilating gas mixtures can be used to simulate different atmospheric compositions that might occur under different fire conditions (e.g., compositions observed when part of the available oxygen has been depleted). Thus, the ventilating gas mixture consists of different proportions of nitrogen, oxygen, carbon dioxide and carbon monoxide. Helium can also be included in the ventilating gas mixture to simulate the atmospheres used in oceanographic hyperbaric chambers.

The fabrication of the outer and inner shells and the sampling section has been completed at this time and these components have been assembled to form the CPTC. The chamber is supported by a mounting structure which also supports the Optical Aerosol Analysis System as well as some of the particle sampling apparatus. Other components which have been installed are the sample mount, the weight transducer, and the radiant heat source. The radiant heat source (Pyropanel by Research Incorporated) consists of a 5 inch square array of four 500 watt tungsten filament quartz lamps with a ceramic reflector. It has been calibrated and found to give a maximum radiant flux of 10 watts/cm^2 at a distance of 1.0 inches from the sample. Design of the flame source has been completed, and it will be installed after testing with the radiant source has been completed.

<u>Combustion Products Sampling and Chemical Analysis System</u>. Two heated isokinetic sampling probes are used to withdraw samples of the combustion products from the sampling section of the CPTC. A schematic of the sample analysis system is shown in Figure 2. The sample withdrawn by one of the isokinetic probes leads to the Anderson Impactor (Model 21-000), which measures particle size distribution for the size range .6 to 11 microns. Part of the sample withdrawn by the other isokinetic probe goes to a Whitby aerosol analyzer (Thermal Systems, Inc. Model 3030) for particle size distribution determination in the range .01 to 0.6 microns, and the remaining part goes to a particle mass measuring instrument (Thermal Systems, Inc. Model 3200B), which measures the smoke particle mass per unit volume of sample. The temperature of the withdrawn samples will be maintained at the temperature that exists in the suspension. The Whitby aerosol analyzer furnishes size distribution measurements every 1.5 minutes during a test while the Anderson impactor furnishes an integrated size distribution for an entire test. After the smoke particles are filtered out of the sample stream, the remaining gaseous products are collected in gas sample bottles for later analysis with the gas chromatograph/mass spectrometer (GC/MS) system. Samples of the solid and liquid particles accumulated in the Anderson impactor (larger than .6 microns) are collected after each test, weighed, and injected into the GC/MS for analysis. Smaller particles which are not caught by the Anderson impactor are trapped by an absolute filter and are later recovered for analysis. The GC/MS system consists of a Hewlett-Packard Model 5930A mass spectrometer coupled to a Perkin-Elmer

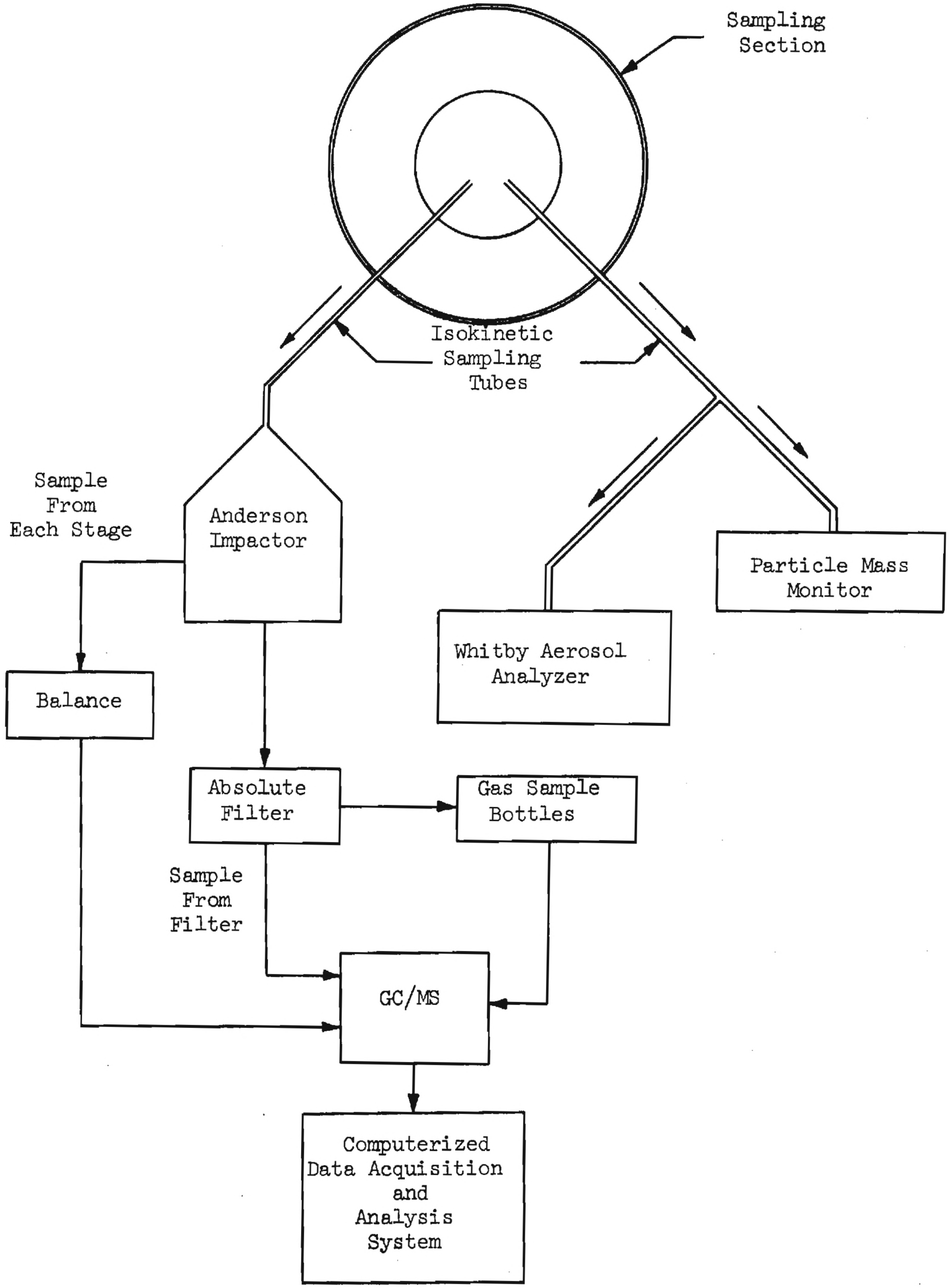

Figure 2. Combustion Product Analysis System.

Model F-11 gas chromatograph. The GC/MS system is also equipped with a Hewlett-Packard data acquisition and analysis system that will record the total-ion chromatograms and the mass spectra. Identification of individual mass spectra will be accomplished using the NIH Mass Spectral Search System, which is provided on the General Electric Mark III Foreground Computer Service.

Most of the equipment needed for the analysis of the combustion products has been obtained and is now being checked out. This includes the sampling probes, the Anderson impactor, the Whitby aerosol analyzer, the particle mass monitor, and the GC/MS system.

Optical Aerosol Analysis System. The optical aerosol analysis system provides a method of in situ size and concentration measurement which can be applied in situations where the accuracy of conventional sampling techniques is questionable. Measurement of scattered blue light at forward angles of 5° and 15° and measurement of attenuation of monochromatic red and blue light gives the average size, index of refraction, and volume concentration of the smoke particles.

A schematic of the optical system is shown in Figure 3. The red light source is a 5 milliwatt helium-neon laser at 6328 Å (Spectra-Physics Model 120) while the blue light source is a 4 watt argon-ion laser (Coherent Radiation Model CR-2) operating at 4579 Å. The laser beams are combined and are directed into the sampling section of the CPTC through a quartz optical window, while the transmitted and scattered beams leave the sampling section through similar optical windows on the opposite side. The transmitted beam is further attenuated by neutral density filters (.001% transmission), focused through a 0.02 inch pinhole to eliminate scattered light, and recollimated before entering the photoelectric detectors. A 50-50 beam

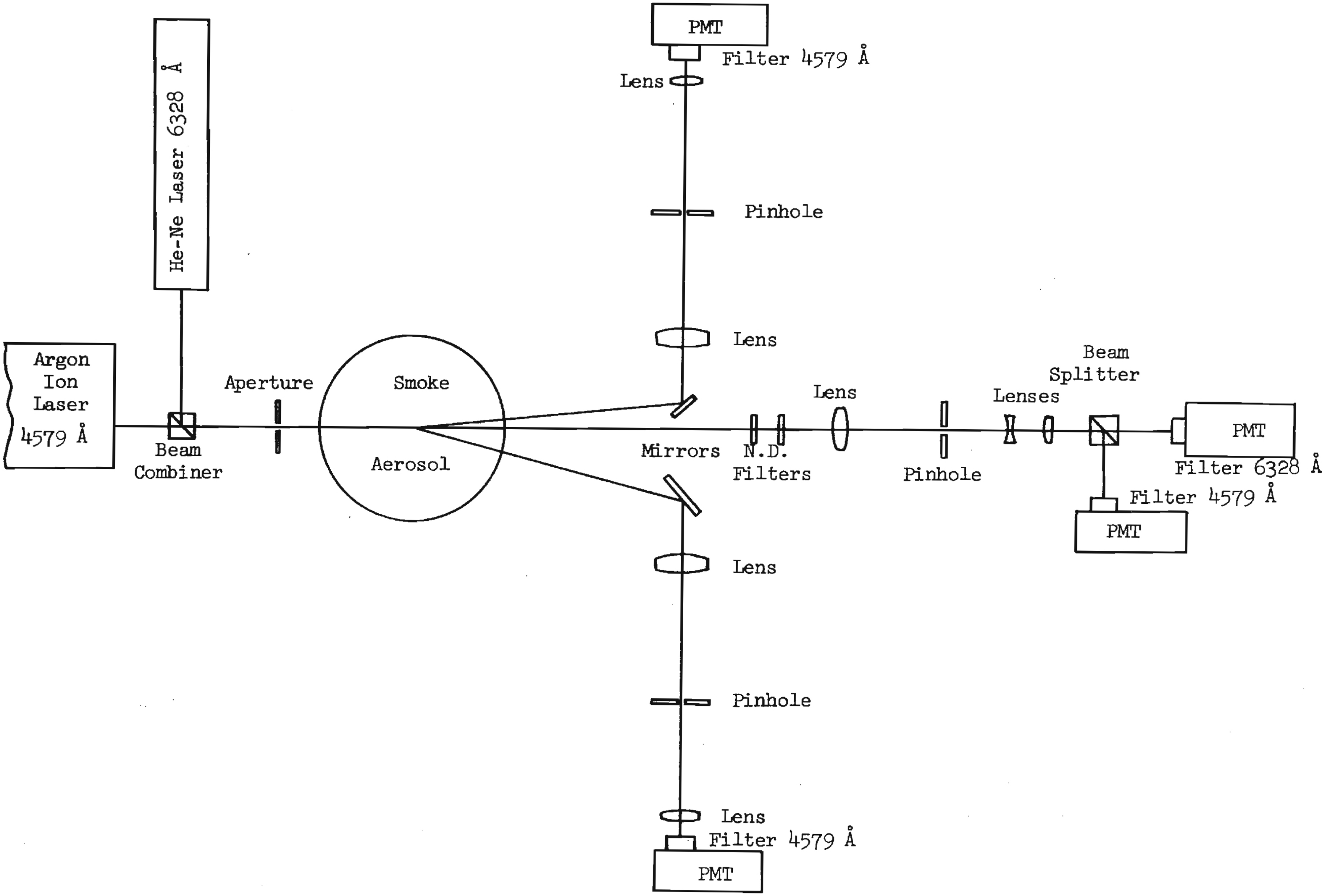

Figure 3. Optical Aerosol Analysis System.

splitter cube sends half of the transmitted beam through a 6328 Å bandpass filter to an EMI 9558C photomultiplier tube for red light detection, while the remaining light is deflected at right angles to an RCA 1P22 photomultiplier tube equipped with a 4579 Å bandpass filter for blue light detection. The scattered beams at 5° and 15° are directed by mirrors to photomultiplier tubes (RCA 1P28 and 1P21) equipped with 4579 Å filters for detection of scattered blue light. Before entering the detectors the scattered beams are focused through 0.02 inch pinholes to limit the detector field of view to 0.3° and then recollimated.

The output of the scattered light detectors is used to determine the ratio of scattered intensities for the two angles which yields the average particle size independently of particle refractive index and concentration. For blue light scattered at angles of 5° and 15° this measurement is applicable for the size range 0.15-2.0 microns. The light attenuation measurements give the ratio of total scattering coefficients for the two laser wavelengths. Coupled with the size determination, the ratio of scattering coefficients yields the refractive index and volume concentration. Refractive index can be determined by this method for particles in the size range 0.25-1.5 microns for refractive indices in the range 1.1-2.0. The average size, refractive index, and volume concentration are calculated from the light intensity data using a computer program based on approximate light scattering functions derived from the Mie theory.

In addition to the laser light scattering/attenuation measurements, conventional optical density measurements using a white light source will also be made. Light from a 100 watt tungsten filament bulb is focused on a 0.04 inch diameter pinhole and collimated by a 300 mm lens to give a 3/16 inch diameter beam. The white light beam passes through the smoke aerosol just below the path of the laser beams and at an angle of 15° to them. An EMI 9601B photomultiplier tube measures the intensity of the transmitted white light to determine the optical density of the smoke.

All of the optical components have been obtained and have been assembled to form the optical aerosol analysis system. The optical components are mounted on optical benches to maintain alignment and the detector array is enclosed in a light-tight box to eliminate ambient light. The lasers and photomultipliers have been calibrated and checked out. Before any samples are tested the entire optical system will be checked out using a test aerosol produced by a dioctyl phthalate (DOP) generator. This generator (Royco Model WA) produces an artificial smoke with a mean particle size of 0.3 micron.

A computer program has been developed to reduce the optical data to determine the characteristics of the smoke. The inputs to this program are the intensities of scattered blue light at two angles and the intensities of the transmitted light at two wavelengths (red and blue). From this information the program computes the average particle size, particle refractive index and particle volume concentration. This program has been checked out on a Univac 1108 computer and has been found to be functioning properly.

ACCOMPLISHMENTS

The following is a list of accomplishments under NSF Grant GI-40782 during the period November 1, 1973 to May 31, 1974.

(1) Construction of the combustion products test chamber, which includes the inner and outer shells, the sampling section, the supporting structure, the sample mount with weight transducer, and the radiant heat source.

(2) Acquisition and checkout of the various components of the sampling and chemical analysis system, which includes the sampling probes, the Anderson impactor, the Whitby aerosol analyzer, the particle mass monitor, and the GC/MS system.

(3) Assembly of the optical aerosol analysis system, which includes the helium-neon and argon-ion lasers, the scattered light optical system and detectors, and the transmitted light optical system and detectors.

(4) Development and checkout of the computer program to determine the aerosol properties from the optical data.

POTENTIAL APPLICATIONS

The facilities which are being developed under this program provide a capability to do valuable research in the field of fire safety. These facilities will be used to analyze and characterize the smoke and gaseous products generated during fires, to determine the circumstances under which severe concentrations of smoke, lachrymators and toxic gases develop, and to develop small-scale testing methods that could be used to predict the characteristics of the combustion products generated in actual fire situations. Data obtained with this facility will aid in the choice of better materials to reduce the hazard from smoke and toxic gases produced during fires in buildings. In addition to fire research, the sampling and chemical analysis system as well as the optical aerosol analysis system can be used in air pollution studies.

FUTURE MILESTONES

It is expected that all of Task I will be completed by the end of June, and that the test program (Task II) will begin in July. The initial test program will concentrate on the determination of the properties of the combustion products generated by burning in gases at room temperatures. In this program wood, polyurethane, and polyvinylchloride (PVC) samples will be tested for different ventilation gas mixtures and with both flaming and radiant ignition sources. These tests are expected to be completed by the end of October.

Future plans are being made for testing at higher temperatures and also for investigating the properties of the combustion products generated by the combustion of a wider class of materials than those tested initially. The experimental data will also be used as a guide in the development of analytical means for the prediction of smoke formation during fires.

UNIVERSITY
OF UTAH

UTEC-MSE 74-083
FRC/UU-29
June 21, 1974

THE PHYSIOLOGICAL AND TOXICOLOGICAL ASPECTS OF SMOKE PRODUCED DURING THE COMBUSTION OF POLYMERIC MATERIALS

Summary Report 1972-1974

I. N. Einhorn
M. M. Birky
M. L. Grunnet
S. C. Packham
J. H. Petajan
J. D. Seader

National Science Foundation
RANN Program/GI 33650

Flammability Research Center
University of Utah
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TABLE OF CONTENTS

THE PHYSIOLOGICAL AND TOXICOLOGICAL ASPECTS OF SMOKE PRODUCED DURING THE COMBUSTION OF POLYMERIC MATERIALS

INTRODUCTION

On April 11, 1972, the University of Utah's Flammability Research Center was awarded a National Science Foundation RANN Grant GI-33650 to support a project entitled, *The physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials.* The effective dates of the initial grant were April 1, 1972 to September 30, 1973. This grant has been renewed until September 30, 1975.

The NSF-RANN program was supplemented by the addition of a two-year grant provided by The Society of the Plastics Industry, Inc. This total two-year award amounted to $83,000. The SPI grant established seven graduate fellowships, provided funds for needed equipment, and provided total support for the task directed toward the "Analysis of Fire Injury by Smoke."

The current project consists of seven tasks organized, as shown in Figure 1 under the direction of Professor Irving N. Einhorn. The current project staff is listed in Table I.

The specific research objectives of the NSF-RANN program are presented in Table II. A unique feature of the program is represented by objective 4 - the development of methodology for determining the physiological consequences of smoke and fire exposures. New methodology was necessary since to date, virtually all data on smoke intoxication consisted of LD_{50} results. This program has adopted the position that survival and quality of survival following fire exposure is a much more sensitive and useful way of describing a material's toxicity. Tasks 3, 6, 7, 8, 9, and 10 of this report will reflect this general philosophy.

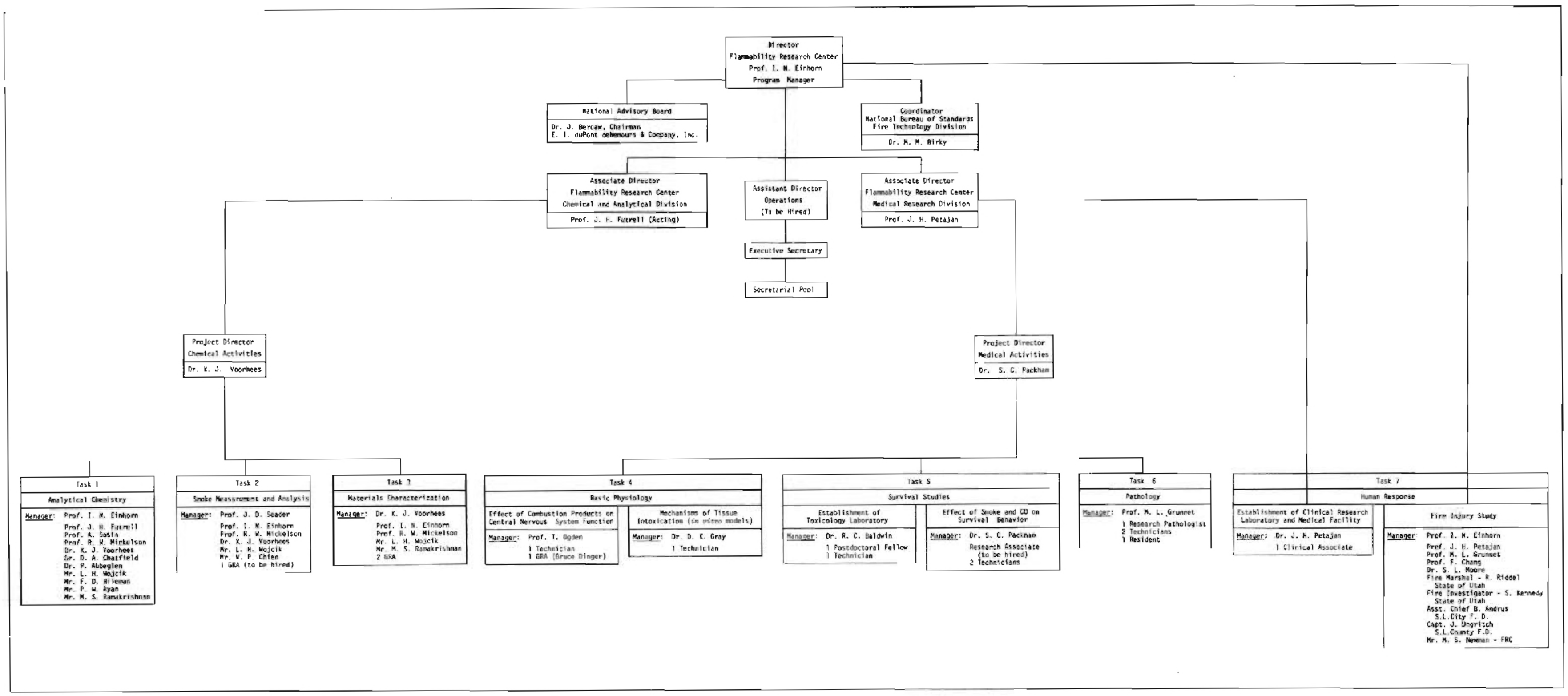

Figure 1. Proposed RANN Renewal Program

TABLE I

NSF-RANN PROJECT STAFF

Program Manager	Professor I. N. Einhorn Flammability Research Center and Division of Materials Science and Engineering
Associate Program Managers	Professor J. H. Petajan, M. D. Department of Neurology Professor J. H. Futrell Department of Chemistry
Project Directors	Professor K. J. Voorhees - Chemical Activities Division of Materials Science and Engineering Dr. S. C. Packham - Medical Activities Department of Neurology
Executive Secretary	Ms. L. M. DeVeer Division of Materials Science and Engineering
NBS Coordinator	Dr. M. M. Birky National Bureau of Standards
Chairman - Advisory Board	Dr. J. R. Bercaw E. I. duPont deNemours and Company, Inc.

Senior Program Staff

Dr. P. C. Abbeglen (Computer Science)
Department of Chemistry

Professor R. C. Baldwin (Toxicology)
Division of Materials Science and Engineering

Dr. D. A. Chatfield
Post Doctoral Fellow
Division of Materials Science and Engineering
Department of Chemistry

Professor J. J. Comeford
Visiting Associate Professor of
Materials Science and Engineering
National Bureau of Standards

Dr. D. B. Frens
Research Fellow
Department of Neurology

Dr. D. K. Gray
Post Doctoral Fellow (1975)
Department of Neurology

Professor M. L. Grunnet, M. D.
Department of Neurology
Department of Pathology

Professor R. W. Mickelson
Visiting Associate Professor of
Materials Science and Engineering
Wayne State University

Dr. S. M. Moore
Clinical Associate Professor of Pathology
Medical Examiner - State of Utah

Professor T. E. Ogden, M. D.
Department of Physiology
Department of Neurology

Professor J. D. Seader
Department of Chemical Engineering

Professor A. Sosin, Chairman
Division of Materials Science and Engineering;
Department of Physics

Experimental Pathologist
(To be hired)

Fire Injury Study Team

Director
Professor I. N. Einhorn
Division of Materials Science and Engineering

Associate Director
Professor J. H. Petajan, M. D.
Department of Neurology

Staff
Assistant Chief B. F. Andrus
Fire Marshal
Salt Lake City Fire Department

Professor E. Z. Browne, M. D.
Department of Surgery

Professor F. C. Chang, M. D.
Director of Emergency Services
Department of Surgery

Professor M. L. Grunnet, M. D.
Department of Neurology
Department of Pathology

Mr. S. M. Kennedy
Fire Investigator
State of Utah

Dr. S. M. Moore
Medical Examiner
State of Utah

Mr. M. S. Newman
Fire Investigator
Flammability Research Center

Mr. D. M. Pingree
Chief Deputy Fire Marshal
State of Utah

Mr. R. D. Riddell
Fire Marshal
State of Utah

Mr. J. Townsend
Fire Investigator
Flammability Research Center
(Salt Lake City Fire Department)

Captain J. C. Ungricht
Salt Lake County Fire Department

Program Staff

Mrs. N. Beglarian
Histology Technician

Mrs. D. L. Lerdahl
Electron Microscope Technician

Medical Technician
(To be replaced)

Mr. M. B. Hessing
Biological Technician

Biological Technician
(To be replaced)

Toxicology Technician
(To be hired)

Mr. L. H. Wojcik
Analytical Chemistry - Technician

Ms. A. M. Raddatz
Secretary

Graduate Students

Mr. B. D. Buchanan
College of Medicine

Mr. W. P. Chien
Department of Chemical Engineering

Mr. B. G. Dinger
Department of Physiology

Mr. F. D. Hileman
Department of Chemistry

Mr. D. H. Hou
Division of Materials Science and Engineering

Mr. J. B. McCandless
Department of Pathology

Mr. M. S. Newman
Department of Biology

Mr. M. S. Ramakrishnan
Department of Chemical Engineering

Mr. P. W. Ryan
Department of Chemistry

TABLE II

PROGRAM OBJECTIVES - NSF-RANN PROGRAM

1. To provide continuous interaction with Federal, state, and local units of government concerned with the "fire problem."

2. To provide a continuous resource base to state and local Fire Services.

3. To develop analytical procedures and methodology which will better characterize the nature of the combustion process with respect to the smoking tendency of materials and the nature and concentration of smoke.

4. To develop methodology for determining the physiological and toxicological consequences resulting from human exposure to fire and combustion products.

A RANN Advisory Board was established to provide continuous interaction by experts from government, industry, and other flammability research groups. The RANN Advisory Board meets as a full board a minimum of three times a year with the full Flammability Research Center staff. Table III lists the individuals who make up the RANN Advisory Board.

This report presents a brief summary of the major accomplishments during the first two years of program effort.

TABLE III

NSF-RANN ADVISORY BOARD

Dr. James B. Bercaw - Chairman
Assistant Section Manager
Textile Fibers Department Technical Service
E. I. duPont deNemours & Company, Inc.

Mr. George Armstrong
Southwest Research Institute

Mr. James E. Bihr
Managing Director
International Conference of Building Officials

Mr. Jerome P. Carroll
Director of Safety and Loss Prevention
The Society of the Plastics Industry, Inc.

Mr. William C. Darr
Mobay Chemical Company
Division of Raychem Corporation

Dr. Robert M. Fristrom
Program Manager - RANN Program
Applied Physics Laboratory
The Johns Hopkins University

Dr. Clayton E. Hathaway
Monsanto Company
Corporate Fire Group Fire Safety Center

Dr. Paul W. Smith
Chief, Aviation Toxicology Laboratory
Aeromedical Research Branch
Federal Aviation Administration

Dr. Theodore Torkelson
Dow-Chemical Company
Midland Division

Prof. R. Brady Williamson
Program Manager - RANN Program
Department of Civil Engineering
University of California

Dr. John A. Zapp, Jr.
Haskel Laboratory for Toxicology and Environmental Medicine
E. I. duPont deNemours & Company, Inc.

Ex-Officio Members

Dr. Ralph H. Long, Jr.
Advanced Technology Division
National Science Foundation-RANN

Mr. James Gaskill
Lawrence Livermore Laboratory
University of California

Dr. Paul Wright
Medical Department
Monsanto Company

PROGRESS AND SIGNIFICANT ACCOMPLISHMENTS, 1972-1974

Task 1 - Materials Selection and Characterization

The polymeric materials presently under investigation are representative of four classes of materials:

1. Cellulosics (naturally-occurring polymers)
2. Urethanes (thermosetting polymers)
3. Polyvinyl chlorides (thermoplastic polymers)
4. Douglas fir (wood widely used in construction).

These materials were selected because of their widespread and continuing specification as materials used in building and construction applications; their use in automotive, aircraft, marine, and other transportation applications; and their wide-scale acceptance in interior furnishings.

The primary objectives of the first two-year's program was the development of the methodology necessary to characterize and quantify the products of pyrolysis and combustion of the above polymeric materials under conditions typical of those encountered during actual fires. Besides general characterization, four specific phases are included in this study:

1. pyrolysis
2. oxidative degradation
3. smoldering combustion
4. flaming combustion

A substantial fraction of our effort has been devoted to implementation of the computerized analytical system for gas analysis shown schematically in Figure 2.

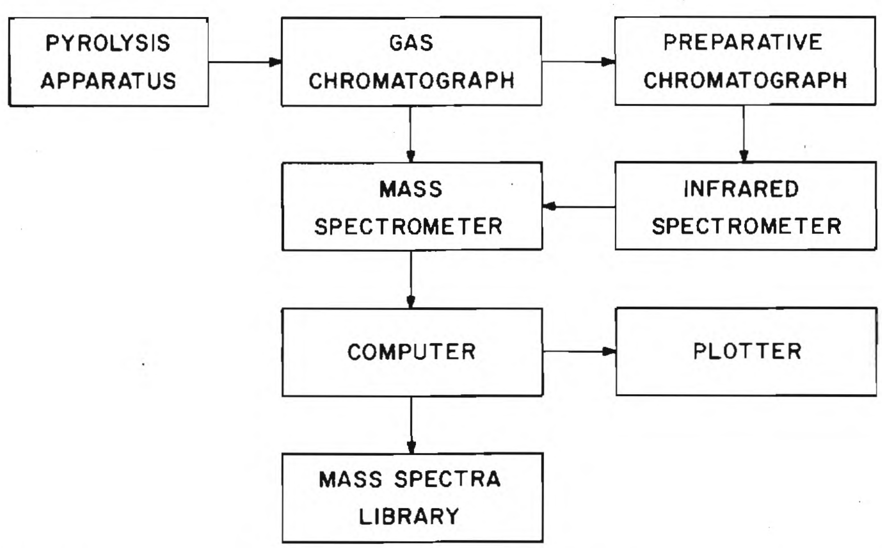

Figure 2. Schematic Representation of Computerized Analytical System

The general characterization concerns the virgin material and consists of: (1) formulation, (2) elemental analysis, (3) physical properties including tensile strength, elongation, compression set, and load-bearing, and (4) flammability characteristics, including smoke development (ASTM-D-2843T), ignition and propagation (ASTM-D-1692 at 45°), flame penetration test, and limiting oxygen index.

Characterization of materials by pyrolysis in an inert atmosphere involves the identification and quantification of the gaseous products by gas chromatography (GC) and mass spectrometry (MS). Depending on the material, different separation columns and detectors are used. The Hewlett-Packard dodecapole mass spectrometer completely scans a mass range of 1 to 600 amu in two seconds. This is fast enough to permit spectral identification of separate GC peaks in real time. As an example, the results from a commercial TDI-based flexible-urethane foam are shown in Table IV. Two mg samples were pyrolyzed at 300°C, 500°C, 750°C, and 1000°C. Chromosorb-101 and Dexsil Columns were used with both thermal conductivity and flame ionization detectors. Peak areas were determined by an electronic integrator. Positive identification was made by computer matching the mass spectra with known spectra from an extensive computerized library. Quantification was achieved by using the chromatograph response factors of Dietz. Table IV shows that the gaseous pyrolysis product composition changes drastically with the temperature.

TABLE IV

PRODUCTS OBTAINED DURING THE PYROLYSIS OF FLEXIBLE-URETHANE FOAM

(Chromosorb-101 and Dexsil Columns)

Product	300°C		500°C		750°C		1000°C	
	μg	%	μg	%	μg	%	μg	%
CO	--	--	--	--	4.45	0.19	44.20	1.65
CH_4	--	--	1.42	.06	9.35	0.41	46.60	1.74
CO_2	6.44	0.21	12.47	.55	3.00	0.13	29.80	1.12
C_2H_4	--	--	0.36	.02	14.07	0.62	39.50	1.49
C_2H_2	--	--	--	--	--	--	0.14	0.05
C_2H_6	--	--	0.84	.04	14.40	0.68	12.00	0.45
H_2O	2.95	0.10	--	--	12.66	0.55	12.40	0.47
C_3H_6	2.49	0.08	31.17	1.38	10.66	0.47	142.10	5.35
CH_3OH	--	--	--	--	0.49	0.02	1.51	0.06
CH_3CHO	Trace		16.05	0.71	42.37	1.86	126.40	4.75
CH_3CH_2OH	--	--	1.13	0.05	2.52	0.11	4.57	0.17
CH_3CH_2CHO	Trace		10.73	0.47	24.05	5.46	279.50	10.40
$CH_3CH_2CH_2OH$	--	--	1.75	0.08	4.39	0.19	10.31	0.38
TDI	7.15	0.23	14.28	0.63	6.35	0.28	11.55	0.41

The effect of environment can greatly influence the mode of pyrolysis and the gaseous species produced. For oxidative degradation studies, a Mettler Thermoanalyzer 1 has been coupled to the GC/MS analytical system. This thermoanalyzer performs thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential thermal analysis (DTA), simultaneously. It is possible to obtain a mass balance by determining an elemental analysis on the virgin material followed by quantitation of the effluent gases and any remaining residue. The effect of environment on the TGA is shown in Figure 3 for a flexible-urethane foam in helium, air, and oxygen. Except in the lower temperature region, the pyrolysis mode under oxidative conditions is much different than that in an inert environment.

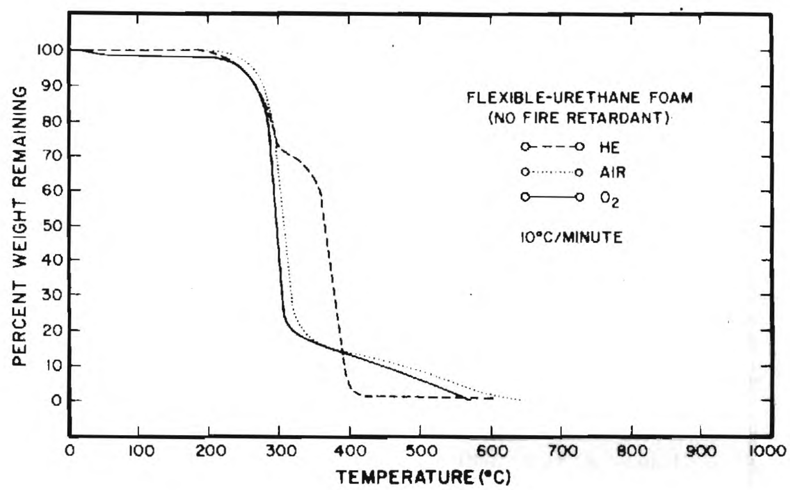

Figure 3. Effect of Environment on Thermal Degradation

Chemical analysis of degradation products resulting from smoldering and/or flaming combustion is extremely complex. In the dynamic fire environment, there is often a rapid heat build-up which is greatly influenced by the presence of an excess supply of oxygen. Under some conditions the degradation products may also provide a fuel-rich environment and this affects the combustion process. In an attempt to develop a model which will permit simulation of the fire environment, additional laboratory studies of flaming combustion have been carried out. Figure 4 presents a comparison of the chromatograms obtained during laboratory-scale pyrolysis and combustion experiments involving flexible-urethane foams. Definite changes in the nature of decomposition products occurred. Of particular significance is the peak identified as hydrogen cyanide in the combustion chromatogram that does not appear in the pyrolysis chromatogram.

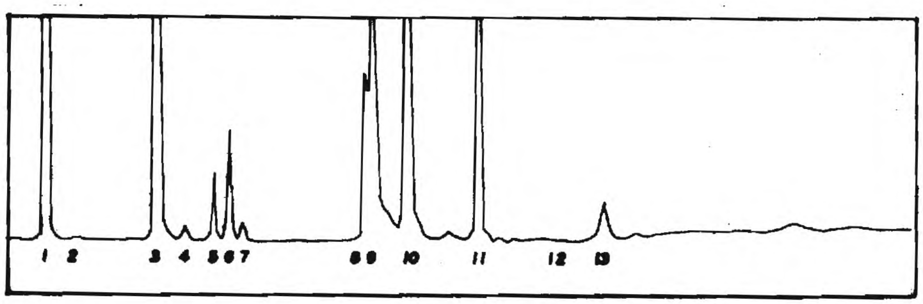

Figure 4a. Combustion, Flexible-Urethane Foam

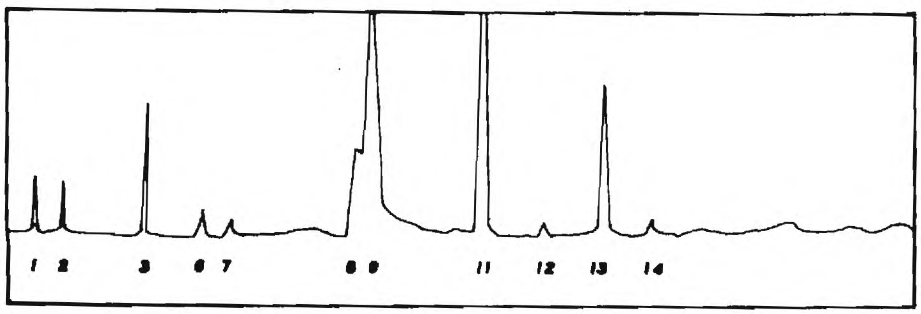

Figure 4b. Pyrolysis, Flexible-Urethane Foam

1. CO
2. CH_4
3. CO_2
4. N_2O
5. C_2H_4
6. C_2H_2
7. C_2H_6
8. H_2O
9. C_3H_6
10. HCN
11. C_2H_4O
12. N.I.
13. C_4H_8

Figure 4. Comparison Degradation Products from Combustion and Pyrolysis of Flexible-Urethane Foam

Task 2 - Development of a Chamber for Smoke Studies

During the first year's effort, two important modifications were made to the Aminco-NBS Smoke-Density Chamber. A weight transducer was installed to permit continuous monitoring of sample weight while measuring light transmittance. A high-energy-flux radiant heater was developed in a cooperative effort with Deltech, Inc. to extend the energy flux operating range from 1.9 watts/cm^2 to 7.5 watts/cm^2. For many materials, this permits tests under auto-ignition conditions. Experiments are now run routinely and reproducibly using both the weight transducer and the high-energy flux heater. Smoke chamber data are recorded by a multi-channel data logger. The data are processed and plotted by a high-speed digital computer.

Modifications made to the chamber during the second year include the installation of a light-filter so as to approximate a monochromatic light source. Data obtained from such a source is more readily treated by light-scattering theory. Also, a particulate filter has been added to the chamber system. It can remove liquid and/or solid particulates as small as 0.015 micron in diameter. This filter permits the determination of the fraction of mass loss that is attributable to particulates. We are now installing in the chamber an oxygen meter, a gas-mixing fan, a gas heater, an inert gas injection system, and a number of temperature sensors.

The NBS-Aminco Smoke-Density Chamber has been used for prototype development of an "Animal Exposure - Smoke-Density Chamber." A slingholder device has been fabricated which permits insertion of one to four rats into the smoke chamber,with appropriate instrumentation to permit continuous monitoring of major vital functions during smoke experiments. A port has been drilled into the wall of the chamber to facilitate withdrawal of blood samples from cannulated animals for analytical purposes during actual smoke exposure.

Several ports have been built into the chamber walls to permit withdrawal of smoke grab-samples for monitoring purposes. Techniques for chemical analysis have been developed which permit qualitative and quantitative analysis of smoke-grab samples utilizing the computerized analytical system.

Task 3 - Development of Animal Exposure Chambers

Several prototype animal exposure chambers have been designed and built during the first two-year's program. The first exposure chamber was a modified Skinner Box encased in an airtight acrylic shell. This chamber was used in the initial feasibility experiments to evaluate the effect of exposure to carbon monoxide on animal physiological response. This chamber was found to have two basic weaknesses: (1) its form produced eddy currents of varying concentrations, and (2) it was inadequately shielded from extraneous 60-cycle AC electrical interference. Modifications were made that remedied these inadequacies. A funnel-like extension to the chamber with appropriate baffles permitted a more streamlined flow of gases during exposure experiments. This modified chamber, illustrated in Figure 5, was then housed in a metal Faraday cage.

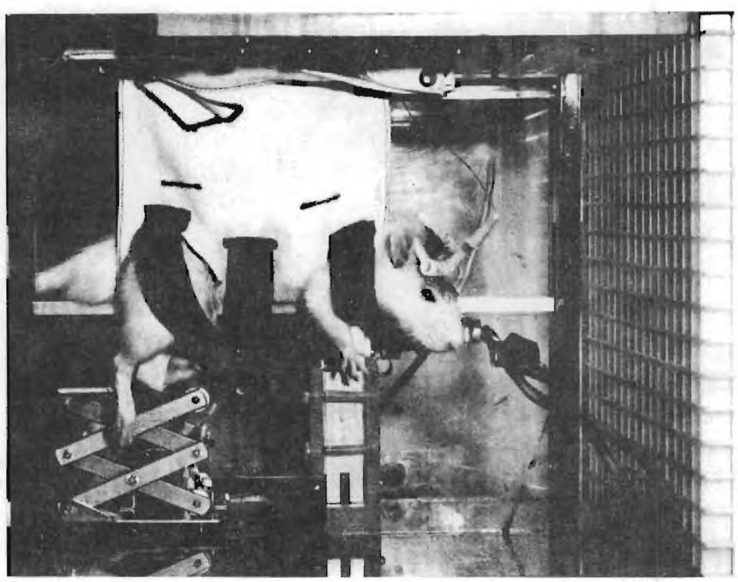

Figure 5. Modified Dynamic Environmental Animal Exposure Chamber

The sling restrainer, shown in Figure 5, was developed to facilitate monitoring of animal vital functions during exposure. By positioning the animal in a fixed position the gas flow profile within the chamber can be monitored and controlled more easily. The modified animal chamber was equipped to provide environmental and physiological monitoring during exposure.

The mode of introducing the intoxicant into the chamber is by dynamic mixing of the intoxicant with air as both are drawn through the chamber. This allows continuous regulation of gas intake and concentration.

A static chamber has been built to supplement the dynamic chamber. This static chamber, shown in Figure 6, is an airtight box into which the intoxicant is placed and allowed to equilibrate by diffusion. The concentration thus remains relatively constant until the chamber is flushed. This chamber is equipped to permit monitoring of the environment, as well as the physiological and behavioral responses of animals exposed to the toxicant atmosphere.

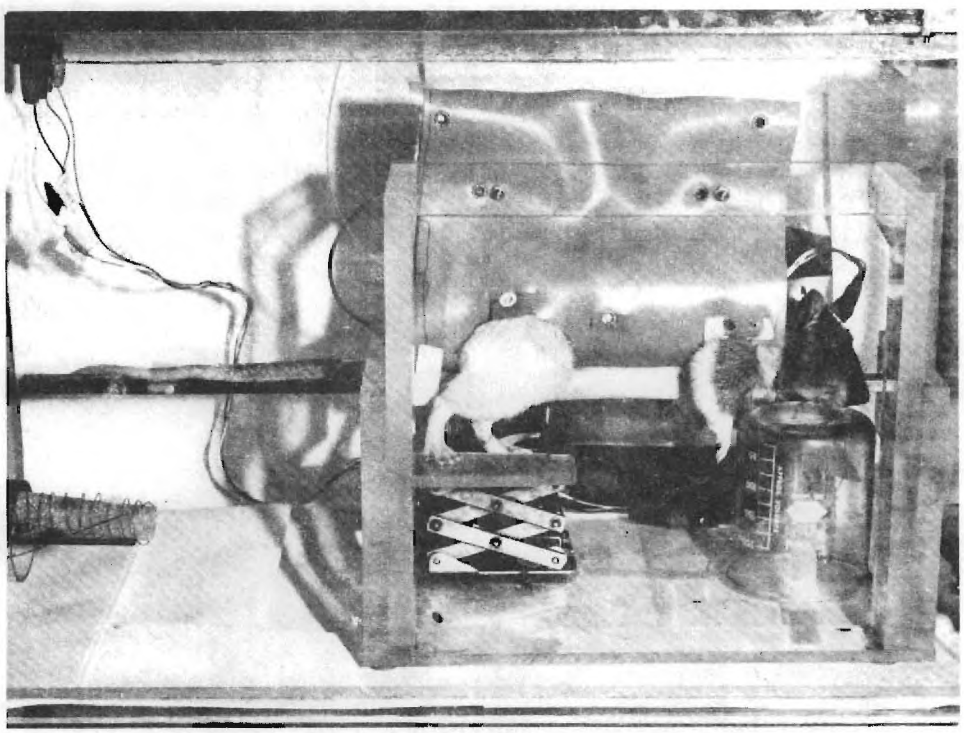

Figure 6. Static Environmental Animal Exposure Chamber

Task 4 - Measurement of Smoke

During the effort of the first year, a total of 104 tests were conducted in the Aminco-NBS Smoke Chamber to measure optical density. Most of these tests included simultaneous measurement of sample weight. In addition, initial tests were run with the high-energy-flux heaters. It was shown that the increase in specific optical density with time corresponded reasonably well to the sample weight loss after allowing for the lag because of the time needed for the smoke to spread through the chamber. The maximum specific optical density was found to increase with energy flux until ignition occurred. Not only is more smoke produced at higher energy flux levels up to the auto-ignition point, but the initial rate of smoke generation is greatly increased. At energy fluxes higher than that required for auto-ignition, the optical density was appreciably lower than in the non-flaming region, for the cellulosic materials tested.

During the second year of the program, 132 additional tests have been conducted with the smoke chamber. Most of these tests have been with polyurethane foams, both fire-retarded and non-fire-retarded. The effects of fire-retardant concentration and energy flux on smoke development have been studied over a relatively wide range.

We are now studying the effect of chamber oxygen partial pressure and space temperature on specific optical density and mass loss.

Utilizing the continuous weighing device incorporated into the smoke chamber during the first year's program, we developed a new smoke correlating parameter called the mass optical density (MOD). The MOD has been shown to be a more fundamental parameter than the widely used specific optical density. Compared to the specific optical density (D_s), the mass optical density is essentially independent of the material thickness and density. However, the mass optical density is dependent on the fraction of airborne mass loss that is particulates (Γ_1).

Figure 7 is a plot of the mass optical density as a function of time for a number of materials under standard non-flaming conditions. Significant differences in the positions of the curves are noted with the wood and α-cellulose samples occupying a central position.

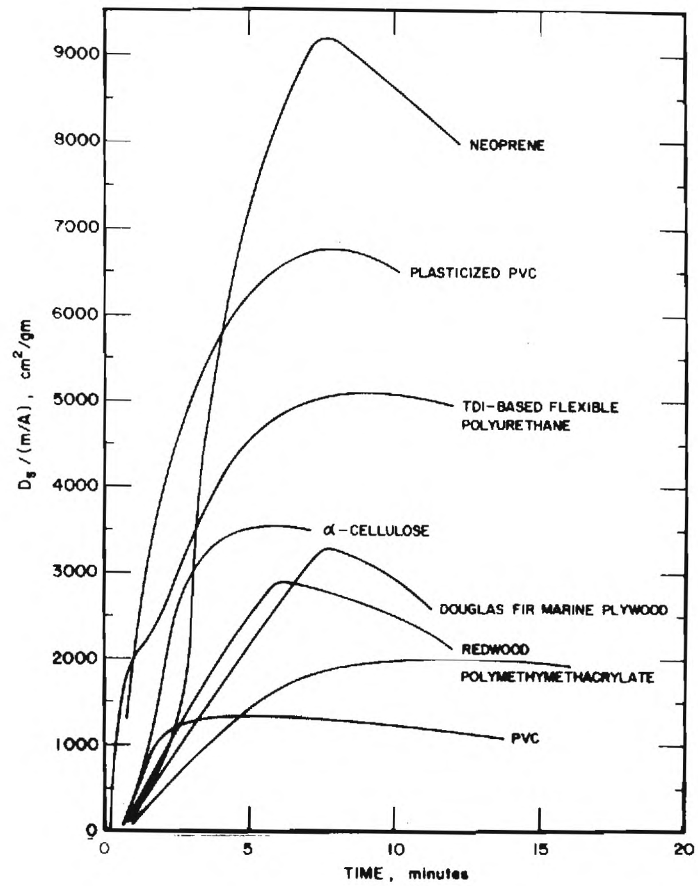

Figure 7. Mass Optical Densities of Several Materials.

Task 5 - Analysis of Smoke

The computerized analytical system described under Task 1, together with a combustion chamber and a sample collection apparatus, comprise the principal investigative tools employed in the qualitative and quantitative analysis of smoke resulting from polymer pyrolysis and combustion. Because of the wide variety of major and trace products encountered with the different polymeric materials, it is necessary to develop individually-tailored analytical schemes.

Major attention has been focused on the identification of species. Originally, this was accomplished by matching mass spectra. However, some difficulty was encountered with species of the same mass units. Consequently, an additional chromatographic identification parameter, the retention index of Kovat, has been adapted. Unlike the retention time, the retention index (RI) is not dependent on column length or gas flow rate. The RI is dependent on the nature of the column and to a limited extent, on the temperature. A variety of compounds of interest have been run on the Chromosorb-101 column and identified by relating them to a normal hydrocarbon coinjected with the sample. Table V lists RI values for a number of species on Chromosorb-101.

TABLE V

RETENTION CONSTANTS - CHROMOSORB-101

COMPOUND	CARBON NO.	COMPOUND	CARBON NO.	COMPOUND	CARBON NO.
NITROGEN	0.52	2,2 DIMETHOXYPROPANE	5.13	BENZENE	7.09
OXYGEN	0.57	FURAN	5.14	3-BUTENENITRILE	7.09
CARBON MONOXIDE	0.59	ETHANENITRILE	5.46	PENTANAL	7.16
METHANE	1.00	PROPENENITRILE	5.62	DIHYDROPYRAN	7.20
CARBON DIOXIDE	1.48	2-METHYL-2-PROPANOL	5.62	2,5 DIMETHYLFURAN	7.25
NITRIC OXIDE	1.76	1-PROPANOL	5.69	BUTANENITRILE	7.25
ETHENE	1.83	DICHLOROMETHANE	5.69	METHYLCYCLOHEXANE	7.55
ETHYNE	1.94	2-METHYL-PROPANAL	5.80	3,3 DIMETHYL-2-BUTANONE	7.64
ETHANE	2.00	2-BUTANOL	5.82	2-METHYL-TETRAHYDROFURAN	7.80
PROPENE	2.95	1-PROPENE-3-OL	5.87	1-OCTENE	7.99
PROPANE	3.00	2-METHYL-PROPENAL	5.88	OCTANE	8.00
PROPYNE	3.30	BUTANAL	5.89	CYCLOPENTANOL	8.14
DIMETHYL ETHER	3.50	3-METHYLPENTANE	5.92	TOLUENE	8.23
METHANOL	3.66	HEXANE	6.00	PYRIDINE	8.28
METHANAL	3.70	2-BUTANONE	6.16	2,4 DIMETHYL-3-PENTANONE	8.32
ETHANAL	3.91	2-PROYN-1-OL	6.19	NONANE	9.00
BUTANE	4.00	2-BROMOPROPANE	6.28	1-NONENE	9.05
1-BUTENE	4.00	2-METHYL-FURAN	6.28	O-XYLENE	9.12
k,2 EPOXYETHANE	4.11	PROPANENITRILE	6.30	ETHYLBENZENE	9.17
TRANS 2-BUTENE	4.17	TETRAHYDROFURAN	6.38	ETHYNBENZENE	9.38
CIS 2-BUTENE	4.24	2-BUTEN-1-OL	6.60	STYRENE	9.53
BROMOMETHANE	4.30	3-BROMOPROPENE	6.67	M-XYLENE	9.56
ETHANOL	4.52	1-BUTANOL	6.71	P-XYLENE	9.56
PROPENAL	4.97	2-BUTENAL	6.76	DECANE	10.00
PROPANAL	4.98	1-BROMOPROPANE	6.80	1-DECENE	10.03
PENTANE	5.00	CYCLOHEXANE	6.92	N-PROPYLBENZENE	10.09
2-PROPANOL	5.01	3-METHYL-2-BUTANONE	6.93	BENZALDEHYDE	10.60
DIETHYL ETHER	5.03	1-HEPTENE	6.99	BENZONTITRILE	10.69
ACETONE	5.09	HEPTANE	7.00	UNDECANE	11.00

Since Chromosorb-101 was designed for the separation of light organic materials (M.W. <150), a series of other columns have been used in preliminary smoke studies to detect higher boiling constituents. A Chromosorb-103 column was used to specifically analyze for any nitrogen-containing compounds. Also, Carbowax 20M and Dexsil 300 GC columns were used to separate the higher boiling pyrolysis products. The Dexsil column proved to be extremely useful in that it has low column bleed and readily elutes the toluene diisocyanate released from flexible-urethane foam during pyrolysis.

The quantitative gas analysis that can be achieved with our analytical system has been used to determine the mass balance. The results indicate that smoke particulates, including condensates, may be appreciable, because the total gas accounts for only a fraction of the mass loss. In order to study this problem, a large-scale pyrolysis unit (Figure 8) was constructed to allow the collection of any involatiles or heavy materials. This unit consists of a sealed 2" O.D. pyrex tube with ground glass fitting and side arm. The cap for the tube has electrical feed-throughs and tube insert for flushing with an inert gas. A three-neck flask is connected to the tube's side arm and various condensers can be used with the unit to trap the condensable products. The side arm is normally packed with glass wool to trap any particulates. Heating is accomplished using a michrome wire coil. With flexible-urethane foam, a yellow condensate has been recovered. The amount of this condensate and its relatively high nitrogen content permit a closer mass balance check. The infrared spectra of the yellow residue shows a strong ether stretch at 1100 cm^{-1} and a carbonyl-urethane stretch at 1730 cm^{-1}. This suggests that within the yellow residue a portion of the urethane structure is still intact. Analysis of the exact nature of this structure and the distribution of the nitrogen will be the subject of future research.

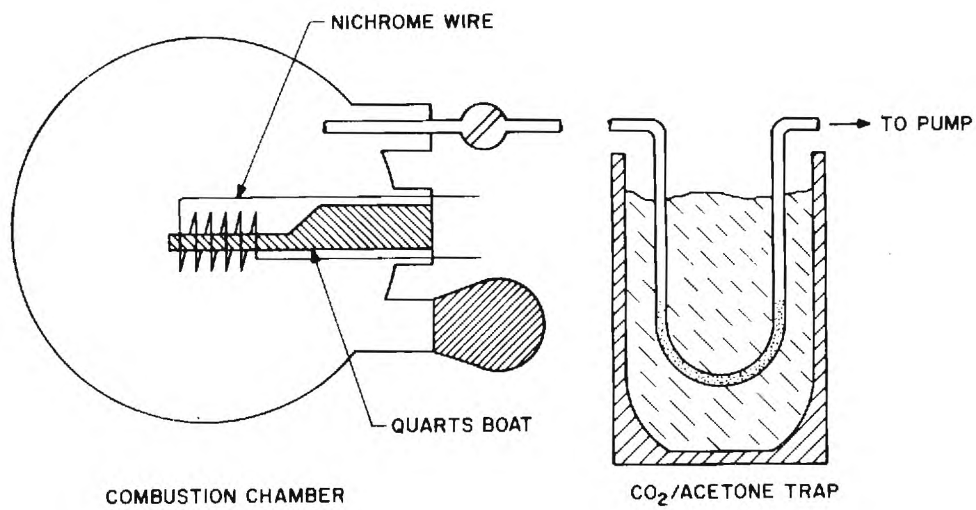

Figure 8. Large-Scale Pyrolysis and Combustion Apparatus

Task 6 - Effect of Fire Retardants on Smoke and Degradation Products

To date, the major concern of those engaged in the development of fire retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet code and regulatory requirements regarding flame spread. However, it is our opinion that the total hazard resulting from incomplete combustion may actually have been increased. A study of several recent fires, in which fire-retarded plastics were involved has indicated that smoke development and the production of copious amounts of toxic decomposition products have resulted in bodily injury or loss of life long before the spread of fire has reached those individuals trapped in the conflagration.

The Mettler Thermoanalyzer has been used to conduct experiments on the effects of environment, heating rate, and % fire retardant in urethanes. Figure 9 shows dynamic TGA curves at different bromine fire-retardant concentrations with rigid-urethane foam.

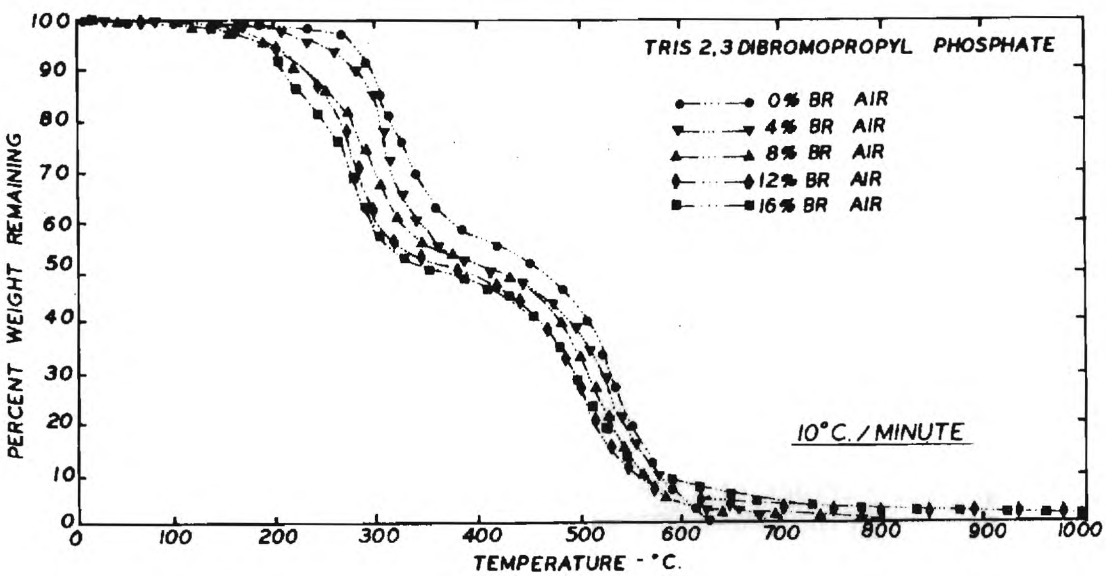

Figure 9. Effect of Fire Retardant Concentration on Thermal Degradation

Overall degradation reaction kinetics are being determined by the ratio method of Mickelson and Einhorn. Major inflection points in the dynamic TGA curves are studied in more detail in isothermal runs with the thermoanalyzer. Smoke tests with the NBS chamber can also be conducted at heat-flux conditions corresponding to these inflection points.

Figure 10 shows the relationship between the final mass optical density and the percent fire retardant for a rigid-urethane foam at an energy flux of 7.5 watts/cm^2. Even at this relatively high-energy flux level, ignition did not occur. Also included in Figure 10 is the percent char residual. The brominated fire retardant system gives more smoke. The reactive phosphorus system results in less smoke, and the char residual is greatest.

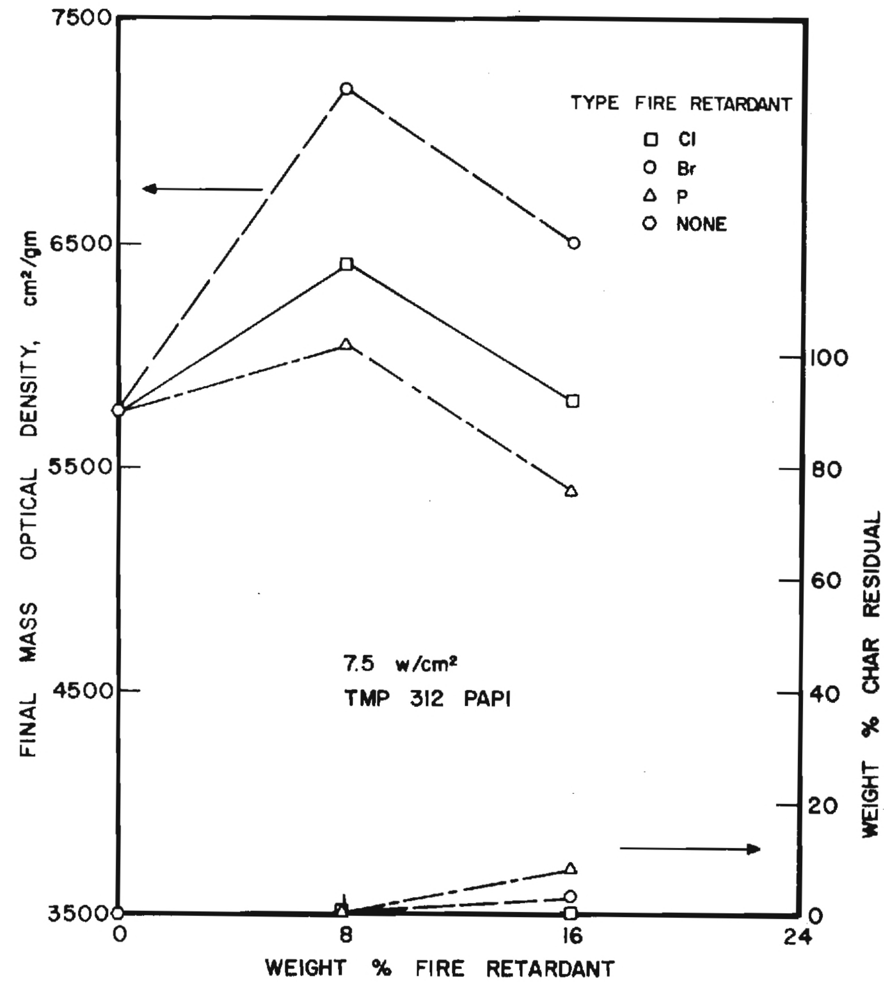

Figure 10. Effect of Fire Retardant Concentration on Final Mass Optical Density at 7.5 watts/cm^2

Figure 11 shows the final mass optical density for 7.5 watts/cm^2 as a function of the limiting oxygen index (LOI). When these data are compared to Figure 10, it is seen that the less flammable polymers (with high LOI) produce more smoke.

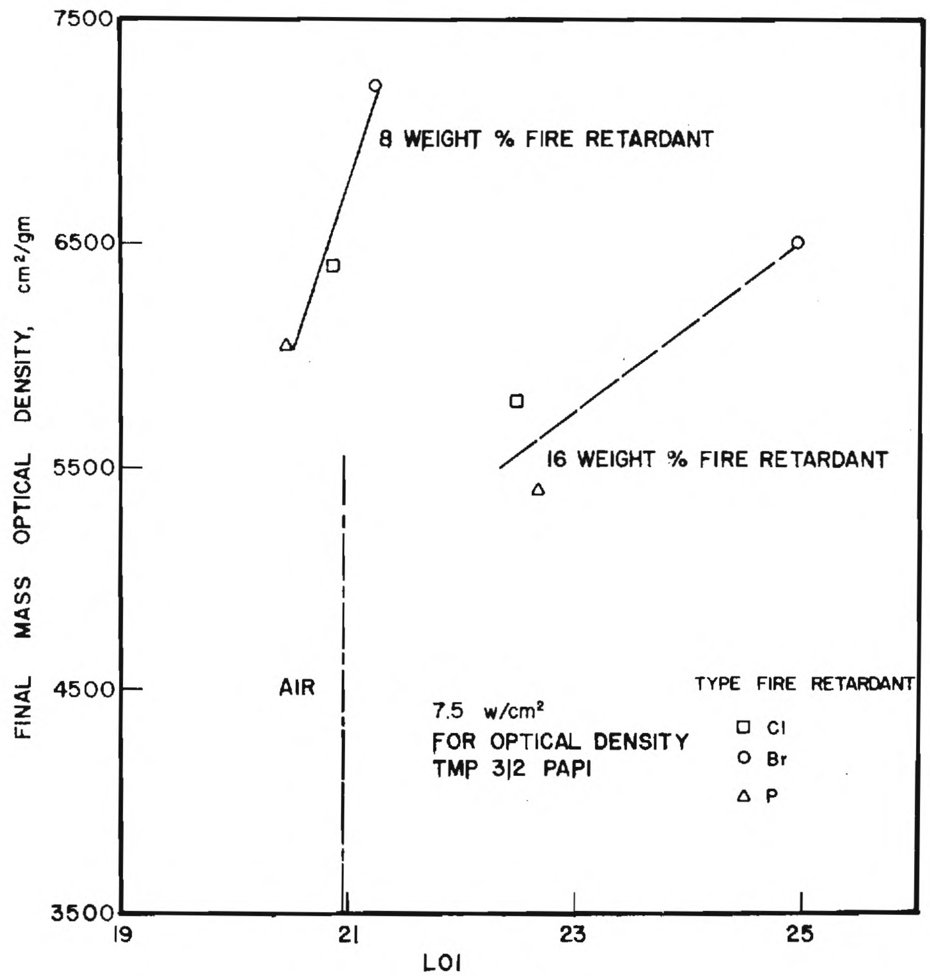

Figure 11. Correlation of Final Mass Optical Density With LOI

Exposure of rats to the products of thermal decomposition of rigid-urethane foams, with and without fire retardants, in the modified NBS smoke chamber has also been carried out. Two fire retardants have been studied at the 16 percent level, namely tris 2,3 dibromopropyl phosphate and reactive o,o-diethyl N,N-bis (2 hydroxyethyl) aminomethyl phosphonate with five gram samples at 5 watts/cm^2 for 20 minutes. With the non-fire-retarded foam, no pulmonary edema or serious physiological effects occurred. With the fire-retarded foams, all animals experienced convulsive behavior indicative of CNS toxicant. Although pulmonary edema occurred in just one case, post-mortem results showed hemorrhagic thymus and lungs. With the reactive fire retardant, all animals died within 15 minutes post exposure.

A static animal exposure chamber was built and used to expose rats to the combustion products of fire-retarded rigid foams. The chamber is approximately 20"x12"x12" giving a volume of 45 liters. A combustion probe has been installed in the wall of the chamber for generation of the combustion products. Numerous electrical feed-throughs are available for monitoring of animal vital functions (heart rate, respiratory rate, blood pressure, and EEG) on a 4-channel physiograph. Two experiments have been run. The initial goal was to approximate the conditions of the tests in the NBS smoke chamber. In the first experiment, 0.475 gm of rigid foam containing 16 percent o,o-diethyl N,N-bis (2 hydroxyethyl) aminomethyl phosphonate was ignited and burned until the sample was charred extensively. The animal exhibited mild hyperactivity, however, exploratory behavior and righting reflex were normal. The EEG recording during the experiment showed no gross abnormality. Breath holding was observed during the exposure as evidenced from the recording.

The second experiment involved the same material under smoldering combustion conditions. The sample size was 0.479 gm. At 40 minutes (20-minutes post exposure), the animal experienced myoclonic jerks and at 45 minutes, brief grand mal seizures occurred. The major motor seizures noted in this experiment were less severe than the grand mal seizures observed from exposures in the NBS chamber, in which case status epilepticus occurred. This is most likely a concentration time or disage phenomena.

Task 7 - Gross Physiological Effects of Smoke

A methodology permitting continuous monitoring of gross physiological activity, i.e., heart rate, respiration, blood pressure, and electroencephalogram (EEG), during smoke exposure, has been developed during the past year. This methodology has required (1) the development of surgical techniques, and (2) the development of instrumentation for recording amplified electrophysiological activity free of 60-cycle AC interference. Surgical procedures include (1) the placement of an intra-arterial cannula in the femoral artery, (2) subcutaneous stainless-steel suture wire electrodes for sensing cardiac and respiratory activity, and (3) the placement of epidural stainless-steel electrodes for monitoring the electrical activity of the brain.

The cannulation system consists of a 25-centimeter piece of PE-10 Intramedic polyethylene tubing with a blunted 30-gauge needle inserted into one end. Anesthesia and control of pulmonary secretions are achieved by simultaneous intraperitoneal injection of sodium phenobarbital, 35 mg per kg, and atropine sulfate, 0.08 mg. The animal is fully alert, mobile, and feeding within four to six hours. The cannula system offers no hindrance to the animal as evidenced by their tendency to leave it unmolested. Throughout the time of exposure, arterial blood can be easily, rapidly, and repeatedly removed with the use of tubing extending from the cannula system to the outside of the exposure chamber.

The ability to measure COHb and O_2Hb rapidly is essential both to the study of carbon monoxide intoxication in animals, as well as the evaluation of patients in comatose or semicomatose states. For this purpose we have procured an Instrumentation Laboratories Model IL-182 Co-oximeter. It has been shown to be reliable in the rapid determination of COHb and O_2Hb in human blood. However, considerable modification of this spectrophotometric technique was required in order to make it routinely applicable to rapid analysis of rat blood. Since the rapid method is not available in any hospital in Utah, the equipment in our laboratory is being used in the evaluation of patients with suspected carbon monoxide intoxication. A log is being kept of these cases.

Clinical data, including a description of the circumstances of the injury, are also being compiled. Such injuries are not only common in association with fires, but also are all too common in the West, where camping at high altitude is a favorite pastime. Figure 12 represents a typical COHb loading curve developed in our laboratory using a cannulated animal and IL-182 Co-Oximeter.

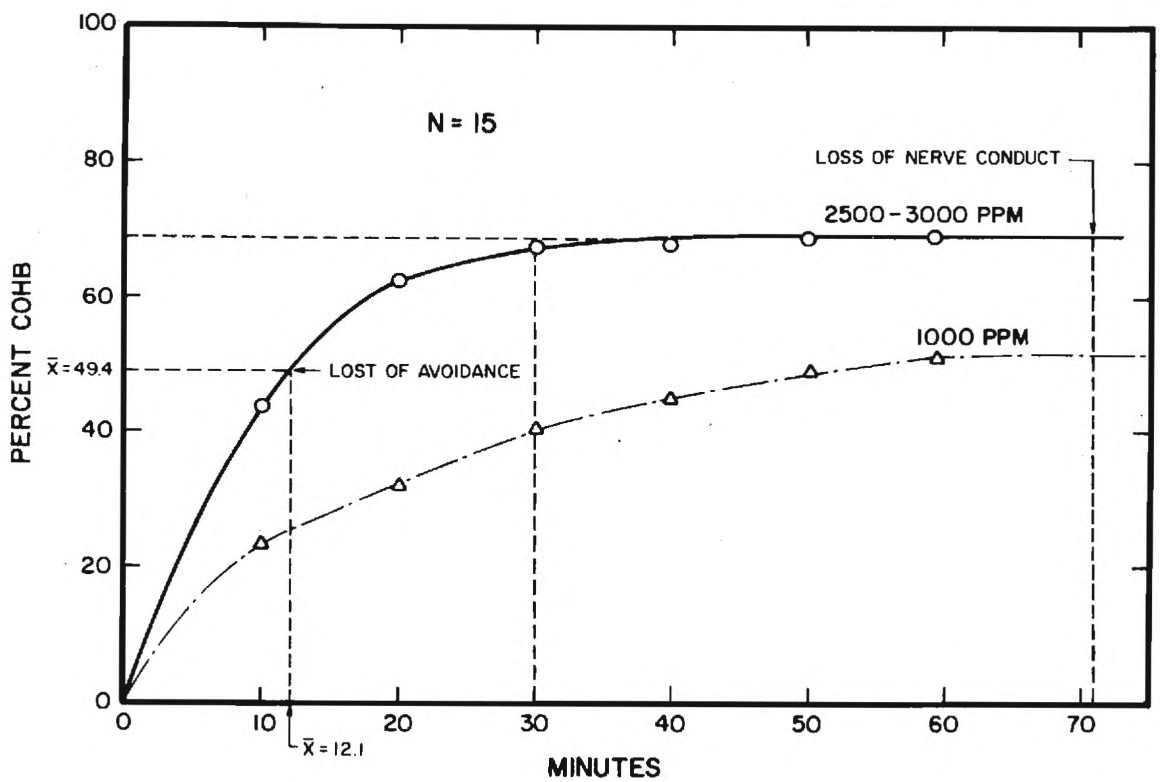

Figure 12. Carboxyhemoglobin and Oxyhemoglobin Loading Curve

Task 8 - The Influence of Volatile Degradation Products of Combustion on the Survival Response of the Rat

Given that fire starts in an occupied building or dwelling, the effect of smoke upon the ability of the occupants to escape becomes the most critical factor. Research undertaken in Task 8 has been directed at development of an experimental procedure which would permit assessment of the relative toxicity of materials and combustion products with respect to their debilitating effects on performance of "survival" type behavior. To this end an animal model has been developed which permits the simultaneous monitoring of behavior and the gross physiological parameters.

During the past year, avoidance from pain-eliciting stimuli has been studied, using a modified Horridge Conditioning Paradigm. The Horridge Paradigm is composed of two parts. In the first, or learning situation, the control and the experimental animals receive shocks dependent on the leg position of the experimental animal (a yoked control procedure). The second stage is the testing situation; the control and experimental animals each receive shocks dependent on the position of his own leg.

The Horridge paradigm has three advantages: (1) it includes a yoked control procedure, a highly acceptable experimental procedure to demonstrate learning; (2) it uses instrumental avoidance conditioning which is a very efficient form of learning, i.e., animals learn quickly and retain the response for days; and (3) the leg position response is readily learned by many species, i.e., dog, cat, rat, monkey, and even insects. A fourth advantage specific to our interest in smoke intoxication, is that the animal can be maintained in a fixed location, being semi-restrained in a sling, as discussed under Task 2.

To date, our interest has been in the debilitating effects of carbon monoxide and smoke upon the performance of a "survival" type response. A shock is delivered to the animal each time his leg position drops to bring his paw into contact with a platform.

Our research has shown that there are various levels of intoxication resulting from exposure to carbon monoxide, namely: (1) ataxia, (2) loss of avoidance behavior, (3) motor collapse, (4) anoxic shock with suppressed respiration rate and cardiac arythenia, and (5) death. A major finding has been that level 2 is not rigidly dependent upon a critical COHb level, but rather is strongly affected by the rate at which the COHb levels are reached.

If animals are taken to the 50 percent COHb level in 10 to 15 minutes, all will lose the ability to maintain an avoidance response. However, when subjects are allowed 45 to 50 minutes to reach the 50 percent COHb level, they are able to maintain their avoidance response throughout the intoxication period (Figure 13).

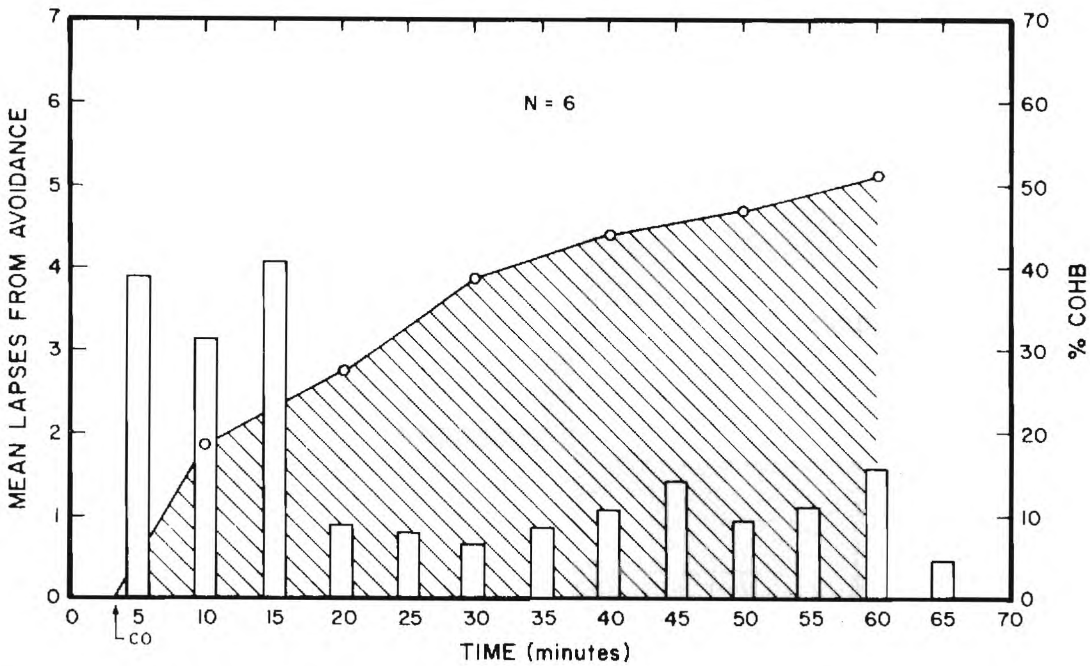

Figure 13. Effect of Rate of CO Intoxication on the Avoidance Response

Other experiments have shown that the ability to perform an avoidance response depends on the chronological sequence of the training and exposure, i.e., whether the training of the response occurs before, during, or after the 50 percent COHb level is attained. Control subjects were trained for 15 minutes, followed by a 30-minute rest period, before a 5-minute test session was started. Avoidance scores during the test session showed the retention of previous training. In comparison it was noted that the avoidance behavior was significantly impaired in animals that were pretrained for 15 minutes and then subjected to a 50 percent COHb level with a 45 to 50 minute period of time for equilibration. Paradoxically, if the subjects were allowed to equilibrate to the 50 percent COHb level in the same 45 to 50 minute period prior to training, and then training introduced, 100 percent of the animals could learn the response. If these same subjects were given 45-minute rests, but maintained the 50 percent COHb level during the rest period, they showed retention of the response. These results indicate that the process or development of intoxication to a 50 percent COHb level is more disruptive to performance than is a 50 percent COHb level, which is maintained for an equal period of time. From these data it becomes clear that one cannot meaningfully speak of critical levels of COHb inducing a particular dysfunction without qualifying the rate of intoxication.

Task 9 - Toxicological Studies

As discussed under Task 6, the NBS smoke chamber has been modified so that rats in groups of four can be exposed to smoke with simultaneous recording of vital functions and removal of small samples of blood for determination of carboxyhemoglobin and oxyhemoglobin. The rats are contained in a sling apparatus that will accommodate four animals placed radially nose-to-nose, for uniform exposure. Simultaneous measurement of smoke characteristics has accompanied each experiment. While it is feasible to use the NBS chamber, it presents certain obstacles to animal monitoring. Therefore, the static exposure chamber has been equipped with a device which permits combustion of small amounts of materials at variable heat flux. When a limiting toxicant has been discovered by use of the NBS chamber, experiments have been carried out in the static chamber, where more detailed physiological observations have been made.

Preliminary experiments have been carried out in the NBS chamber on fire-retarded and non-fire-retarded urethane foams at a heat flux of 5 watts/cm^2. Non-fire-retarded foam produced no behavioral or physiological effects other than those which could be predicted from the COHb values produced (approximately 30 percent after 20 minutes). The amount of eye or respiratory tract irritation was minimal in animals exposed to the control foams. Animals which were exposed to fire-retarded urethane foams exhibited epileptic activity leading to grand mal seizures. Carboxyhemoglobin values have been found to be below 15 percent and oxyhemoglobin levels to be in the range of 80 to 90 percent. Thus, CO-induced anoxia or hypoxia cannot be considered an adequate explanation for this phenomenon.

Using the static chamber and an animal with implanted electrodes for recording the electroencephalogram, high amplitude spike and polyspike activity was produced, which became more frequent and culminated in a typical grand mal pattern associated with a grossly evident grand mal seizure in the animal. Simultaneous electrocardiogram and respiration measurements revealed only some early respiratory irregularities, interpreted as breath holding. No cardiac arrhythmias were observed.

Task 10 - Neuropathological Aspects of Fire Exposure

When rats are exposed to the "anoxic shock" level of carbon monoxide intoxication, they develop a carboxyhemoglobin level of from 60 to 80 percent. Clinically, these animals show a decrease in blood pressure, decreased and irregular respiration, cardiac arrhythmias, and a decrease in ventral caudal nerve conduction velocity. If removed from the CO environment, they survive. The ventral caudal nerve conduction velocity returns to normal in from two to eight days. Sensory conduction is most impaired. Although animals show no weakness during recovery, they are hypersensitive to stimuli.

Ventral caudal and peroneal nerves from rats exposed to the anoxic shock level of CO intoxication were examined 7, 10, 14, 21, and 28 days after exposure. Light microscopy of the nerves did not reveal any abnormalities to account for the decreased conduction velocity. However, with electron microscopy, changes were seen at the node of Ranvier, both in large and small myelinated nerve fibers. The changes were more severe in large myelinated fibers than they were in small fibers.

The speed of progression of damage and repair depended on the size of the fiber and somewhat on the individual animal studied, but the steps in the progression appeared the same for large and small fibers.

Normally a thin sheet of cytoplasm from the Schwann cells on either side of the node or finger-like processes from the Schwann cells make contact at the center of the node. After exposure to CO, the major portions of cytoplasm from the Schwann cells from both sides of the node appear to retract and disengage. The myelin terminals and adjacent myelin are completely or partially destroyed in many large fibers, with myelin figures appearing in the Schwann cell cytoplasm and axoplasm.

From 7 to 10 days after exposure, the process of destruction seemed almost complete in large myelinated fibers but was still going on in smaller fibers. From 14 to 28 days the finger-like projections of Schwann cell cytoplasm began to reappear at the node (Figure 14).

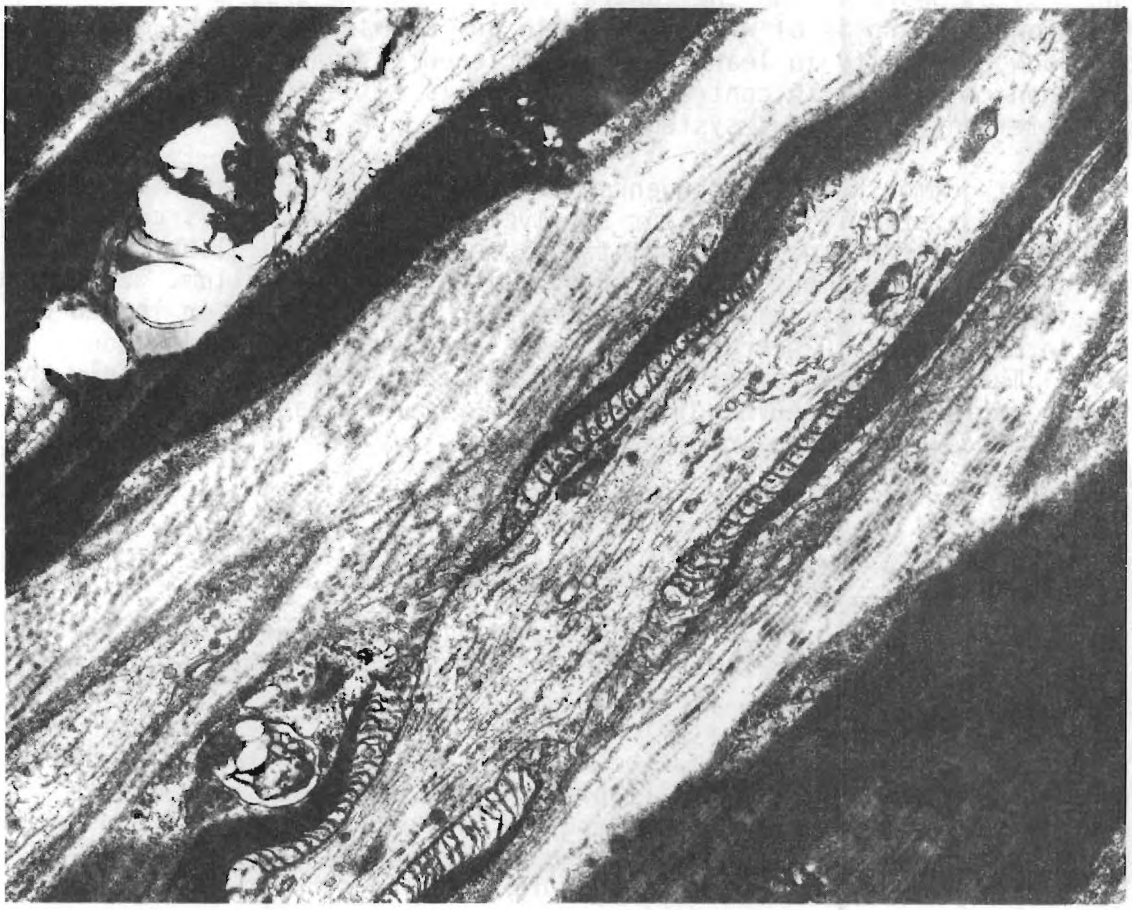

Figure 14. Node of Ranvier 21 Days Post Exposure to Anoxic Shock Level of CO Poisoning, Showing Return of Finger-Like Processes, but an Elongated Node and Myelin Debris in the Schwann Cell (Longitudinal Section 6000 X)

Complete joining of thin layers of Schwann cell cytoplasm or finger-like processes from either side of the node overlying vertically-oriented finger-like processes was not often seen. When joining was seen there was often re-duplication of Schwann cell basement membrane over the node. The total process of reconstitution of destroyed myelin terminals and Schwann-cell structures at the node was not observed. The node was rarely completely repaired by 28 days post exposure.

We have studied the brains and spinal cords of rats exposed to the anoxic shock level of CO intoxication at various times after exposure by light microscopy only. Six animals were studied 7 days after exposure, two animals 14 days after exposure, two animals 21 days after exposure, nine animals 28 days after exposure and four animals two months after exposure. There was no apparent loss of neurons from the central nervous system grey matter or demyelination or necrosis of white matter in any animal. However, exposed rats did show difficulty in learning a conditioned response 30 days after exposure when compared with control rats. This is evidence that CO probably produced some central nervous system damage.

The most common human consequences of CO poisoning are seen in the central nervous system if the patient survives long enough. This consists of loss of neurons, astrocytosis and sometimes, necrosis of the globus pallidus, cerebral cortex, hippocampus and Purkinje cells of the cerebellum. But there is variation in pathology not completely related to the degree or length of exposure to CO. About 10 percent of patients who survive, show "pseudo-recovery." That is, they appear to awaken from coma and normalize, only to deteriorate mentally and neurologically weeks or months later. This is usually due to delayed demyelination and necrosis of the central nervous system white matter.

Task 11 - Visual Aspects Dependent on Smoke Exposure

Using the static chamber, rats instrumented for measurement of the visual-evoked response (VER) have been exposed to carbon monoxide sufficient to produce anoxic shock, i.e., approximately 70 percent. Thus far, six animals have been studied, and studies are continuing. Paired stimuli (light flashes) 100 msec apart have been used. Computer averaging of 164 responses revealed a clearly identifiable response when electrodes were placed over the occipital cortex. Latency of the primary response did not change significantly despite loss of background cortical activity; the response was still present but attenuated for several minutes after the electroencephalogram became isoelectric and the animal was in shock. Simultaneous blood pressure determinations have been made, in order to differentiate hypoxic from ischemic effects.

Of considerable interest is the effect of carbon-monoxide-induced anoxia upon the second evoked response. The readiness of the cortex to respond to a second flash is effected at lower carboxyhemoglobin levels. Cortical recovery and threshold for response are affected both by the level of cortical metabolism and ascending projections from the reticular formation, and diffuse projection systems from the thalamus, which "tune" the cortical neuron threshold. The second response is attenuated and then lost prior to loss of background activity. It will be a sensitive indicator of visual system impairment. Considerably more data are needed to establish critical carboxyhemoglobin levels for alteration of this response. It may be possible to determine a change in the absolute refractory period of the second response with progressive intoxication.

These studies, when completed, will allow interpretation of data derived from smoke exposure experiments. For example, rats exposed to smoke from fire-retardant foam have an exaggerated response to light flash or noise stimulation. Early intoxication may be manifested as a reduction in cortical threshold to a variety of stimuli.

Task 12 - Large-Scale Fire Tests

In order to obtain information on the behavior of floor coverings (mainly carpeting) under conditions simulating a real building fire, full-scale experiments are being carried out in a corridor-test facility at the National Bureau of Standards. The primary objective of the program is to determine the nature of the hazard associated with carpeting and underlayment in a fire situation, and the relationship or non-relationship of this hazard to current test methods and small-scale laboratory measurements. One of the ultimate goals is the development of a test method that takes into account the hazard associated with combustion gases and smoke. The results of this program are also being interfaced with the toxicological program at the University of Utah. The corridor facility is instrumented at numerous points for measurement of temperature, heat flux, air flow, smoke density, and gas sampling.

Two gas sampling techniques were used to assess the corridor atmosphere during the tests: (1) continuous measurement of O_2, CO, and CO_2 concentrations, and (2) grab samples for collection in pre-evacuated 2-liter flasks for laboratory analyses. In addition, continuous measurements of HCl were made on a vinyl sheet flooring material. A technique is also under development for continuous measurements of HCN.

Figure 15 shows typical carbon monoxide, carbon dioxide and oxygen data for a wool and a nylon floor covering material for a ventilation-controlled fire. In most of the experiments a "gas phase flashover" occurred.

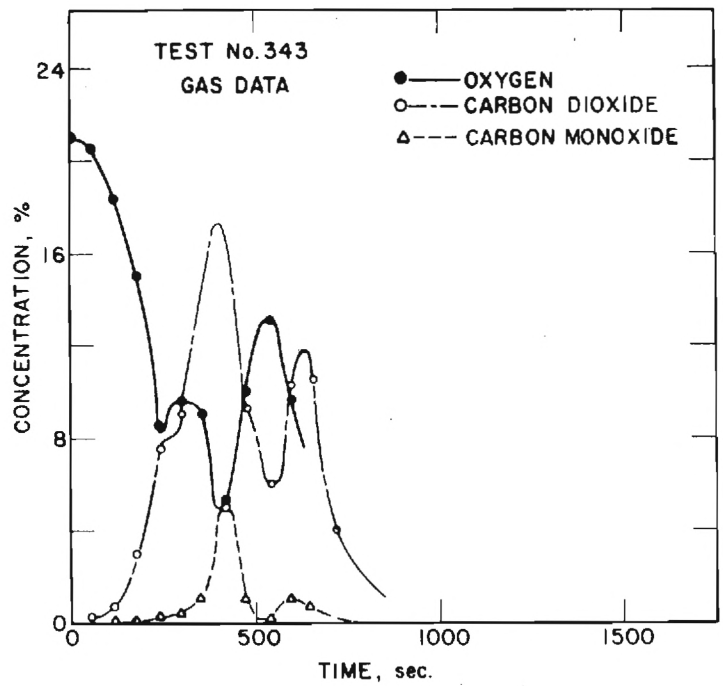

Figure 15. Results of Continuous CO, CO_2, and O_2 Measurement from Wool Carpet

The results of the continuous hydrogen chloride measurements during a test with a vinyl sheet flooring material are shown in Figure 16. The areas burned and charred, as determined by temperature measurements and estimated by visual observations during the test, are overlaid on this graph. The correlation, although not exact, is fairly good. The grab samples were also used for analysis of O_2, CO_2, CO, CH_4, C_2H_4, C_2H_2, and HCN, using infrared spectroscopy and gas chromatography. Large concentration gradients for CO, CO_2, and O_2 existed in the corridor. However, the relative hazard of CO versus O_2 depletion should be valid.

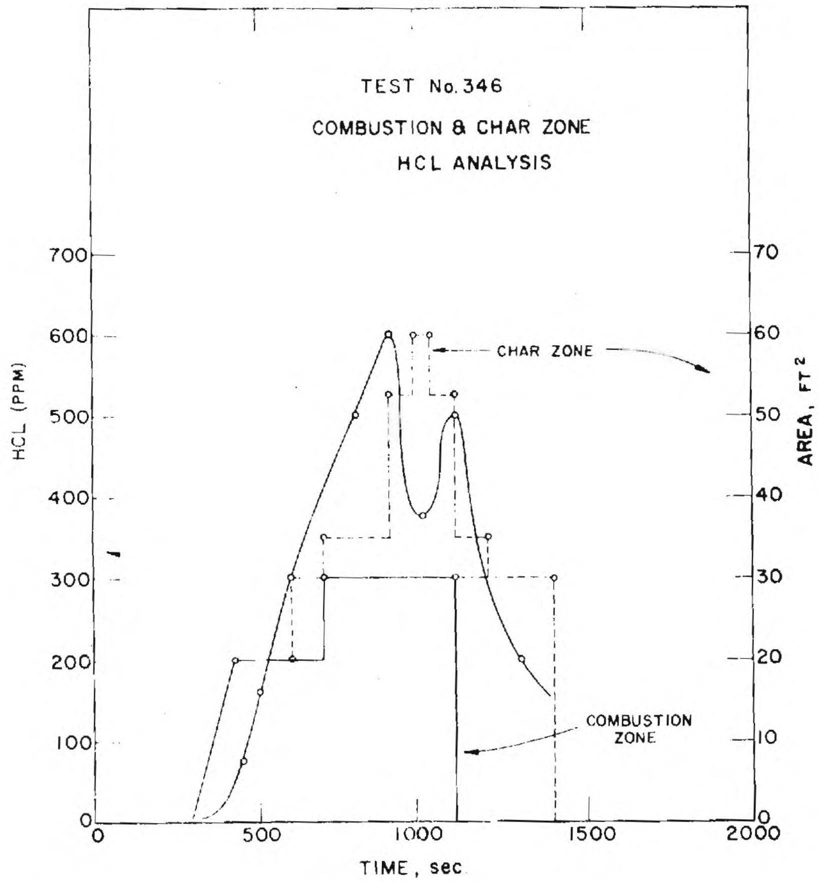

Figure 16. Results of Continuous HCl Measurement

The time required to reach 80 percent optical attenuation as measured across the corridor was chosen as an untenable level from the standpoint of escape and inhalation. In most of the experiments, this time was somewhat less than five minutes. However, lachrymal effects of irritating products on the eyes may occur earlier. Based only on the carbon monoxide concentrations, one has something less than ten minutes to leave the corridor, however, the smoke level by the 5-minute mark is quite severe and perhaps beyond the survival limit except very close to the floor. These data would suggest that the smoke hazard is as serious as the carbon monoxide and combining this with the very rapid oxygen depletion suggests a survival time less than either hazard alone would indicate. The hazard that exists in another room connected to the corridor may not be oxygen depletion, but CO.

Another hazard that contributed to the observed rapid flamespread rate was the "gas-phase flash-over" phenomena. There were significant concentrations of methane, ethylene, and acetylene in the grab samples, particularly at the time when "flash-over" occurred. The rapid flame spread down the corridor appeared to be a gas-phase phenomenon.

What insights and guidance can be obtained from these experiments for developing a laboratory-scale test or model that is realistic and assesses the hazard? If a laboratory measurement of the amount of smoke produced from a floor covering material such as in the NBS-Aminco smoke box is to be realistic, then the dependence or independence of smoke quantities on oxygen availability must be determined in the light of the extensive oxygen depletion found in the corridor. Perhaps smoldering combustion and flaming combustion conditions will actually be the boundary extremes that represent the maximum and minimum smoke-producing conditions and it will not be necessary to control the atmosphere in the smoke box. Is the production of HCN, HCl and other toxic products enhanced in the limited oxygen atmosphere? Is there a correlation between smoke production and carbon monoxide? The hazard associated with the rapid "gas phase flash-over" must also be investigated.

Task 13 - Analysis of Fire Injury

The objectives of the smoke injury studies may be divided into the following three areas: (1) the determination of injuries caused by smoke; both short range and extended illness leading to death, (2) evaluation of the etiology of death by smoke or smoke constituents as evidenced by post-mortem examination, and (3) a detailed investigation program that has been established in cooperation with state and local fire service personnel. The State Medical Examiner coordinates the complete medical examinations of fire victims.

Specific attention is directed toward the qualitative and quantitative analysis of blood alcohol levels, carboxy- and oxyhemoglobin levels, presence of drugs or barbituates, and the presence of heavy metals such as tin, lead, and antimony. Where possible, gas samples are collected for analysis.

To date, twenty fires in which smoke played a major role in causing injury or death, have been investigated. The causes of fire for 18 deaths were:

Cause of Fire	Lives Lost
Cigarette	8
Careless use of matches	5
Flammable liquids	4
Miscellaneous	1
	18

Approximately ten additional cases are in various stages of completion.

Forty-two fires involving fabric-related injuries have been investigated. Two deaths occurred. Approximately 15 additional cases are in various stages of completion.

With the assistance of the Salt Lake City Fire Marshal and the Computer Science Department, fire statistics for 1969 and 1970 have been analyzed.

The fires are characterized as to (1) time of occurrence, (2) equipment involved, (3) source of ignition, (4) flammable material involved, (5) form of material, and (6) property loss. Analysis of the information obtained thus far indicates it may be possible to more strategically locate fire stations and during peak periods of fire occurrence, to permit temporary distribution of fire-fighting equipment and personnel to areas of high potential incidents.

A more extensive program has been formulated for developing fire statistics on a regional basis. Utilization of statistics obtained in the proposed manner would serve as the basis for effectively evaluating large-scale public education programs pertaining to fire prevention and control. It should be possible to overlay on a computer graphic screen, such factors as climatic variations resulting in fire, the effects of building structure, and the effect of socio-economic factors on fire occurrence.

Other Accomplishments

Members of the project staff have interacted strongly with federal, state, and local government, as well as with the public. Project personnel have been invited to participate as expert witnesses before the National Commission for Fire Prevention and Control, the Federal Trade Commission, the Federal Aviation Administration, and the Legislative Council of Utah. The principal investigator was named a member of the Committee on Fire Research of the National Academy of Sciences - National Research Council, a Deputy Fire Marshal for the State of Utah, and a Special Consultant to the Salt Lake City Fire Department.

A major continuing public educational program was initiated by the project staff in May 1972. Numerous public appearances were made before state government committees, the Legislative Council, the Utah Fire Protection Board, in the public schools, and before the general public. An intensive public awareness program was conducted in cooperation with the press and radio and television media. Several tragic fires were discussed on television.

Ancillary activities have resulted in the development and promulgation of the first state standard for the safe use of cellular plastics in building and construction applications. A second state standard has been promulgated regulating the use of cellular plastics in mobile homes and recreation vehicles.

PUBLICATIONS AND REPORTS

The following summary presents a list of recent publications and reports which have resulted from NSF-RANN-sponsored research. These reports have been presented to a wide variety of scientific, engineering, and medical audiences.

REPORTS BASED ON THE RESEARCH CONDUCTED UNDER NSF-RANN GRANT GI-33650

FRC/UU-1 "The Use of Room and Corridor Tests in Predicting Fire Parameters," M. M. Birky and M. J. Marks - paper presented at 1973 Polymer Conference Series, Fire Prevention and Control - A Major Societal Problem, University of Utah, Salt Lake City, Utah (June 1973).

FRC/UU-2 "Monitoring Weight Loss in a NBS Smoke-Density Chamber," W. P. Chien, J. D. Seader, and M. M. Birky, *Fire Technology, 9*, 4, pp. 285-298 (November 1973).

FRC/UU-3 "Methods for the Identification of Products of Combustion of Polymeric Materials - A Computerized Analytical System" I. N. Einhorn and J. D. Seader - paper presented at 1973 Polymer Conference Series, Flammability Characteristics of Materials, University of Utah, Salt Lake City, Utah (June 1973).

FRC/UU-4 "Smoke and Survival During Fire Exposure," I. N. Einhorn - paper presented at American Chemical Society National Meeting, Chicago (August 1973).

FRC/UU-5 "Analysis of Smoke and Combustion Products," I. N. Einhorn - paper presented at Fourth International Fire Protection Association Meeting, Geneva, Switzerland (October 1973).

FRC/UU-6 "Techniques for Computerized Identification of Combustion Products," I. N. Einhorn, F. D. Hileman, and P. W. Ryan - paper to be presented at American Chemical Society National Meeting, Philadelphia, Pennsylvania (October 1974).

FRC/UU-7 "The Effects of Exposure of the Rat Peripheral Nerve to High Levels of Carbon Monoxide," M. L. Grunnet - paper presented at The American Association of Neuropathologists, Freeport, Bahamas (June 1973).

FRC/UU-8 "Neuropathological Studies of Sprague-Dawley Rats Exposed to Acute Concentrations of Carbon Monoxide," M. L. Grunnet and J. H. Petajan - paper presented at Fourth International Fire Protection Association Meeting, Geneva, Switzerland (October 1973).

FRC/UU-9 "Effect of Carbon Monoxide on Skeletal Muscle," J. H. Petajan and J. B. McCandless - paper presented at the meeting of the Federation of American Societies for Experimental Biology, Atlantic City, New Jersey (April 1973).

FRC/UU-10 "Physiological and Pathological Effects of Carbon Monoxide on the Nervous System of the Rat," J. H. Petajan and M. L. Grunnet - paper presented at 1973 Polymer Conference Series, Flammability Characteristics of Materials, University of Utah, Salt Lake City, Utah (June 1973).

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SUMMARY FOR

NSF/RANN Fire Research Conference

Atlanta May 28-29, 1974

RAND INSTITUTE

Institution: NYC-Rand Institute

Grant Title: Fire Research Needs and Priorities

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Project Objectives and Plan: This project seeks to develop a coherent sense of what the nation's major fire problems are and of how important they are relative to competing claims for money and attention. It also aims to develop systematically information that can show whether fire research is, or could be, of major value to the nation, and to provide a process to determine what the priorities for research should be.

The research consists of systematic steps to: identify major problem areas, combing fire-related questions from four vantage points; relate in a programmatic framework problem areas having key elements in common; assess, so far as possible, the importance of potential solutions to the problems, both in absolute terms and relative to programs unrelated to fire aimed at similar broad objectives (such as saving lives); translate these assessments into needs for fire research; develop and structure the criteria into operationally useful terms; develop a process to employ these criteria in determining priorities.

Progress Report: Work to date has developed a number of analytic and synthetic methods and structures designed to facilitate (a) comparison and analysis of fire problems and potential research areas already identified and (b) comprehension and synthesis of new problem and research areas. Technical areas have been examined thus far in moderate detail, emphasizing particularly various frameworks for pulling together otherwise disparate insights into scientific, empirical, and practical phenomena.

Social areas, hitherto the subject of much less research, have been examined thus far in some depth, emphasizing potential linkages with eventual policy. Three areas are receiving particular scrutiny: economic incentives; social incentives; and social regulation, including liability and public nuisance laws. Also being examined in some depth are the interfaces between technical and social problem areas--and potential research on those problems, and the policy levers--existing or conceivable--for translating research results into actions.

74

73

Detailed analysis of the relative importance of fire and fire problems is nearly complete. An extensive study of fire deaths has compared possible life savings relative to other life saving programs. Using detailed demographic analysis, it reveals how many more people could be living at every age if fire deaths were to be eliminated, and compares the current investment per potential life saved with comparable figures for other causes of death. Similar results for personal injury and property damage are in final stages of analysis.

B.C.B.